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ABSTRACT

Digital computer simulations for Surveyor and Apollo Lunar Module (LM) spacecraft landing on a model lunar soil have been conducted. The purpose is to provide an estimate of the mechanical properties of the lunar material on which Surveyor I landed, and to compare the expected penetration of Surveyor and LM when landing on the lunar surface. The principal limitations of the study are that only a single soil model, which represents an incompressible soil with internal friction and cohesion, is used and only vertical motions are considered.

Under the assumption that the Surveyor I footpads penetrated the lunar surface 0.25 feet, it is found that the static bearing capacity of the lunar surface must be 6 psi for an object with the dimension of a Surveyor footpad. However, it is not possible solely on the basis of the penetration data to choose between various combinations of the soil parameters which produce such a bearing capacity. On the basis of the Surveyor I footpad penetration it is also concluded that the Surveyor crush block penetrated the surface about 0.4 feet, and that an Apollo LM, landing at the site of Surveyor I, would penetrate the surface less than 0.4 feet, if it landed uniformly on all four legs with a velocity of 10 ft/sec.

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SUBJECT: Surveyor and LM Penetration in a Model Lunar Soil - Case 340

DATE: February 23, 1967

FROM: E. N. Shipley

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TECHNICAL MEMORANDUM

1.0 INTRODUCTION

This report gives the results of a series of digital computer simulations for both Surveyor and the Apollo Lunar Module (LM) spacecraft landing on a model lunar soil. The purpose of the study is to obtain information by which to judge the mechanical properties of the lunar material on which Surveyor I landed, and to compare the penetrations to be expected from LM and Surveyor.

An estimate of the lunar soil properties has already been obtained(1) by a simplified landing-dynamics analysis, supplemented by an examination of the character of the soil seen in the Surveyor I television pictures. In the present work, the simulation of the Surveyor spacecraft is more accurate, but the analysis includes only the observed depth of penetration of the footpads and crush block of Surveyor I. A simulation of the LM landing on the same model soil has been included so that a comparison between the two spacecraft can be made.

There are two fundamental limitations to this study. First, only a single soil model is considered. The model is an incompressible soil whose mechanical properties can be varied over a wide range by means of parameters which describe the characteristics of the soil. This model is compatible with Surveyor I data, including TV observations, but it is not unique. Second, the motion of the spacecraft is limited to the vertical direction.

For both Surveyor and LM, vertical motion prior to touchdown represents an ideal situation; this condition was essentially obtained by Surveyor I. During the actual touchdown, however, the articulation of the Surveyor landing gear assembly requires at least some lateral motion of the footpad relative to the surface, even though the spacecraft center of mass has no lateral velocity. The effect of the landing gear articulation can be estimated under the assumption of frictional forces between the footpad and the lunar surface. It will be shown in a subsequent section that the effect is small and all lateral forces are neglected in the main portion of this study.

[redacted]

Complete three dimensional simulations of the Surveyor landing are being carried out by other groups, also using digital computer programs.[2] An advantage of the one dimensional simulation which is described in this report is that each case requires a relatively short time on the computer. As a result, the landing behavior of the spacecraft can be studied as the parameters which describe the soil are varied over a wide range.

The results obtained from the simulation depend upon the choice of the values of the quantities which describe the spacecraft. In general these values, such as the spacecraft mass, have been chosen to correspond to the Surveyor I mission, and for LM, to correspond to the nominal mission. Most of these quantities, like the mass, the footpad radius, and the shock absorber characteristics, may vary only slightly from mission to mission for Surveyor. However, the results of the simulation are sensitive to the spacecraft touchdown velocity, which, for Surveyor, may vary considerably. The usefulness of these results for future Surveyor missions depends on the degree to which the touchdown velocity differs from the value for Surveyor I, and, of course, on any changes in the spacecraft design.

2.0 SOIL MODEL

All the analyses and computations which are reported in this study were carried out using an incompressible model soil. In this section we will give only a brief description of that model; more detailed description of the model and the origin of the equations used in this section have been given elsewhere.[3] The model which has been used is based on an incompressible soil model described by Scott[4] and is intended to represent the behavior of an actual incompressible soil such as sand.

It has been emphasized that this study is restricted to the use of a single soil model, and that this restriction represents a limitation to the study. There exist other soil models, e.g., a compressible soil[3], for which it may be possible to adjust the parameters to fit the Surveyor I data. It is not obvious how the characteristics of such a model, i.e., static bearing capacity, would compare with the results from the incompressible model used here, nor how the LM penetration would compare. However, it should be noted that the soil model used here is consistent with visual observations of the lunar surface at the Surveyor I landing site.

In general, the resisting force felt when an object penetrates a soil can be separated into two components, a dynamic and an internal component. The dynamic force, which we will call F_d, arises from the acceleration of the soil material. The internal component, F_i, arises from the frictional and cohesive forces of the soil. The function of the soil model is to provide a rational basis for determining the functional form of F_i and F_d.

The soil flow pattern which was assumed is illustrated in Figure 1. For such an incompressible soil the internal force can be written in the form

$$F_i = \pi R^2 (A + Bz)$$

where z is the depth of penetration and πR^2 is the area of the footpad. A and B depend on the properties of the soil and on the dimensions of the footpad which is penetrating the surface. In this study the footpad is considered to be a disk of radius R.

The soil properties which define the internal force are the angle of internal friction, Φ, the cohesion c, and the density ρ. A and B are determined by the soil properties through the relations

$$A = 1.3c\ N_c + \rho g R(0.6\ N_\gamma)$$

$$B = \rho g N_q$$

where g is the local acceleration due to gravity (5.32 ft/sec^2 on the lunar surface) and N_γ, N_c, N_q are dimensionless quantities depending on the angle of internal friction. The values used in this study are given in Table I.

Since F_d derives from the dynamic effects in the soil, A and B completely define the static properties of the soil. The parameter A is, in fact, the static bearing capacity of the soil at zero penetration. The value of A over the range of soil parameters considered in this study is shown in Figure 2. Because of the dependence on the size of the penetrating object, A differs for the LM and Surveyor footpads. The quantity B represents the rate of increase with depth of the static bearing capacity. It depends only on the angle of internal friction (through N_q) and on the density of the soil. Values of B are given in Table II.

The dynamic force on the soil can be written in the form

$$F_d = [(C + Dz)\frac{d^2z}{dt^2} + D(\frac{dz}{dt})^2]\pi R^2$$

The quantity $(C + Dz)\pi R^2$ is an effective mass which depends on the depth of penetration, and differs from the actual mass in the flow because the cross-sectional area normal to the flow is not constant. Consequently, for an incompressible flow, the velocities and accelerations are not constant throughout the flow pattern, and the terms multiplying $\frac{d^2z}{dt^2}$ must be appropriately adjusted. The term $D(\frac{dz}{dt})^2$ represents the force required to accelerate the material added to the flow pattern as the footpad penetrates into the soil.

One obtains the result

$$C = 0.83\rho R$$

$$D = 0.14\rho$$

for the flow pattern given in Figure 1. For an actual soil the flow pattern would be expected to be a function of the angle of internal friction, but in this study we have assumed that the flow pattern does not change (see Reference 3). Values of C and D for Surveyor and LM are given in Table III.

It is important to note that the soil model which has been used assumes that the motion of the penetrating footpad is along a vertical axis. The relationships between force and penetration do not take into account any horizontal motion of the footpad relative to the surface. This limitation is consistent with the scope of this study.

3.0 SPACECRAFT MODELS

It is the purpose of this section to describe the spacecraft models which were used in the computer simulation and to relate these models to the actual spacecraft. The problems of initial conditions and a discussion of the simulation program itself are given in Section 4.

The essential parts of each spacecraft model are the shock absorber, the footpad, and a point mass which represents the entire spacecraft. In these simulations both the footpad and the shock absorber are assumed to be massless. The footpad is taken to be a flat circular pad both for Surveyor and the LM.

The shock absorber transmits the force between the footpad and the spacecraft mass. Since this study is restricted to one dimensional vertical motion, only the vertical component of force from the shock absorber is considered.

A drawing of the Surveyor geometry is shown in Figure 3. The actual spacecraft has three landing gear assemblies of the type shown spaced at angles of 120° around the spacecraft. Since the center of mass is located at the geometrical center of the landing legs, and because the problem is restricted to one dimension, it is appropriate to replace the complete spacecraft by a single landing leg supporting 1/3 of the mass of the spacecraft.

To calculate the motion of the spacecraft one must know the force exerted by the soil on the spacecraft. Because the footpad and shock absorber are massless, the force exerted by the soil on the footpad must be equal to the force the shock absorber exerts on the mass. The characteristics of the shock absorber are known, and the force it exerts on the spacecraft, and equally on the footpad, can be calculated if the relative motion of the footpad and the spacecraft is given.

The Surveyor shock absorber behaves like a combination spring and damper. The force of the shock absorber, F_a, may be written in the form

$$F_a = K_1 + K_2 s + g(s) \left(\frac{ds}{dt}\right)^2$$

where s is the distance which the shock absorber has compressed. The function g(s) which was used in the simulations is shown in Figure 4. The value of the constants K_1 and K_2 were taken to be 180 lbs. and 280 lbs/inch, respectively, for this study.* The characteristics of the shock absorbers vary from unit to unit, and, in addition, the characteristics of a specific unit are temperature dependent. The values used in this study are representative values for the shock absorbers used on Surveyor I at the temperatures which existed at the lunar landing.

As seen in Figure 3 the shock absorber (and the force it exerts) is not vertical. The resolution of the force into vertical and horizontal components depends on the instantaneous geometry of the spacecraft. Moreover, the lower strut of the landing leg can also exert vertical forces. The magnitude of the vertical force in the lower strut depends on the compression (or tension) force in the strut; this can be determined only by a detailed force balance in the horizontal plane at the footpad. Consequently, for a given shock absorber force, the total vertical force exerted on the spacecraft depends on the horizontal force exerted by the soil on the footpad. For Surveyor, horizontal motion of the footpad relative to the surface must occur whenever the landing leg strokes (see Figure 3); in addition, any horizontal velocity of the spacecraft at touchdown will also cause lateral footpad motion. Whenever such motion occurs, the soil exerts a horizontal force on the footpad both because of friction between the soil and the footpad, and because of the necessity for the footpad to plow through the soil once it has penetrated the surface.

As a further complication, the footpad can swivel about its attachment point to the landing leg. This effect has been completely neglected in this report.

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*These representative values and the function g(s) were obtained from F. Sperling, JPL.

The soil model which we have used is not adequate to define the lateral forces which are generated as the footpad plows through the soil. However, it is possible to obtain a solution for the case where the lateral forces arise from a simple frictional force. We write

$$F_f = \mu F_1$$

where F_f is a horizontal force arising from friction, F_1 is the vertical force exerted by the soil on the footpad, and μ is the coefficient of friction. Because of the symmetry of the location of the three landing legs, the lateral forces on the three footpads produce no lateral acceleration of the spacecraft, if initially there was no horizontal velocity and if the three legs stroke in the same way.

Simulations were run to obtain the sensitivity to friction of the penetration of Surveyor footpads in model soils of various characteristics. The results are plotted in Figures 6 through 8. The footpad penetration is shown as a function of the cohesion for different values of μ. The internal friction angle Φ and the density ρ are maintained constant in each figure. Further details on these simulations, which were run under the same conditions as the other simulations described in this report, are given in subsequent sections.

It can be seen in Figures 6 through 8 that variation of the coefficient of friction over the range 0 to 2 produces a change in footpad penetration of approximately 0.25 feet. The lateral forces which were generated depend on the specific conditions but generally run several hundred pounds for $\mu = 2$. There exist no data on the lateral forces generated in a realistic situation with which these results may be compared.

For the remainder of this study, the lateral forces at the footpad will be assumed to be zero. This is done primarily to eliminate the coefficient of friction as a parameter. The limited effect produced on the footpad penetration is evidence that the elimination of lateral forces is not inconsistent with the other limitations under which this study is conducted. Furthermore, the Surveyor footpads are constructed of crushable honeycomb material (see Figure 3). The lower portion of the footpad crushes at 10 psi. On a frictionless surface this level of pressure was not reached, even for simulations on surfaces so hard that no penetration occurred. Consequently, no crushing is expected. The presence of friction at the footpad can increase the observed pressures above 10 psi under some circumstances, but the program does not include the possibility of footpad crushing. The neglect of crushing in the simulation produces only a very small effect on the previously mentioned cases where friction was included, since the pressure exceeds 10 psi by less than 4 psi and for less than .01 seconds in the worst case.

In addition to the footpads, Surveyor interacts with the surface through crushable blocks (see Figure 3). The crush block radius was chosen so that the total force exerted by each block, while actually crushing, was 1,450 lbs. In our simulations the blocks crush whenever the pressure exceeds 40 psi. At lower pressures the crush blocks may penetrate the surface. The force of penetration is calculated in the same manner as that of the footpad and is included in the simulation.

The length of the uncrushed footpad is 8 inches. Penetrations exceeding this amount, less the distance which the block has crushed, are invalid because they imply that the spacecraft structure has contacted the surface. There is no provision in the simulation to account for the resulting forces.

At moderate penetrations of the footpad, i.e., one foot, various spacecraft structural elements begin to contact the surface. The bottom struts of the landing gear assembly and the bottom of the spaceframe, in particular, would interact with the surface if the penetration is as much as one foot. Smaller penetrations may produce the same effect if significant stroking of the landing leg has occurred. Cases which provide Surveyor footpad penetrations greater than one foot do not represent realistic simulations.

For the LM the assumption that there are no lateral forces is also made, but the constraint is not as severe as for Surveyor. If the LM lands with no horizontal velocity, the footpads would not be expected to slide on the surface. More important, the shock absorber is essentially vertical so that the tangential forces do not affect the relationship between the shock absorber force and the normal force. We have neglected completely the secondary struts of the LM landing gear, and we have assumed the main shock absorber is vertical.

The LM shock absorber is made of crushable honeycomb material. In the simulations performed here the honeycomb material is assumed to have ideal characteristics; that is, it does not yield if the pressure is below the crushing level, and it crushes at an arbitrary rate to limit the pressure to exactly the crushing level. The crushing pressure of the shock absorber is a function of the stroke; the function used in this study is shown in Figure 5.

As was done with Surveyor, the LM mass was distributed equally among the four landing legs. In this way the penetration experienced by an LM descending vertically and landing simultaneously on all four footpads can be calculated. This is referred to as the LM 4-legged case. In addition, a worst case situation was calculated in which all the spacecraft mass was used on a single landing leg (LM 1-legged case). This was done to simulate the case where, due to abnormal attitude of the spacecraft or to large lunar terrain slope, one footpad touches down first and bears the brunt of the deceleration process. The penetration observed in this situation affects the stability limit (against overturning) of the LM.

4.0 SIMULATION PROCEDURES

The equations of motion of the spacecraft interacting with the lunar surface are non-linear, and there is no obvious analytical solution. An approximate solution can be obtained by numerical integration of the equations of motion.

If the position and velocity of the spacecraft and its footpads are known at some time t, the equations of the soil and the spacecraft dynamics can be used to calculate the accelerations of the various elements of the system at that time. With the assumption of nearly constant accelerations, the motion of the system can be propagated forward in time by a small increment Δt. This process is repeated until the system comes to rest.

The procedure is made feasible by a computer program for a high speed digital computer. In our case, Δt was chosen as small as possible consistent with reasonable running time, although care was exercised to insure that too small a Δt did not cause rounding errors to dominate. All of the results reported in this paper were run with a Δt of 0.0002 seconds. The average machine time required for each simulation was about 25 seconds on an IBM 7044 computer.

The calculation has two distinct modes which depend on the action of the shock absorber. In the Active Mode, the shock absorber is stroking, while in the Rigid Mode, the shock absorber behaves like a rigid structure.

The Rigid Mode is characterized by force levels which are too low to activate the shock absorber. For Surveyor this corresponds to a force lower than the pre-load force; once the Surveyor shock absorber begins to stroke, the Rigid Mode is not reestablished until the shock absorber fully extends to its initial position. For the LM the Rigid Mode is used whenever the force levels are below that required to initiate crushing of the leg shock absorber.

In the Rigid Mode the footpad, spacecraft, and soil move as a single entity. If M_e is the effective mass of the soil slug ($M_e = [C + Dz]\pi R^2$), M_s is the mass of the spacecraft, and F_i is the internal force of the soil, then the acceleration, d^2z/dt^2, of the center of mass of the spacecraft is given by

$$\frac{d^2z}{dt^2} = \frac{M_s g - F_i - \pi R^2 D\left(\frac{dz}{dt}\right)^2}{M_s + M_e} \qquad \text{(Rigid Mode)}$$

where g is the lunar gravitational acceleration; the effect of gravity on the soil slug is included in F_i.

In the Active Mode the shock absorber alone determines the force that is exerted on the spacecraft and the soil. The motion of the spacecraft and the footpad are distinct and must be handled separately. For the LM the force exerted on the spacecraft is just the crushing force of the honeycomb material, but for Surveyor the force depends on the relative position and velocity of the footpad and the spacecraft. In either case, however, the state of the system defines the quantity F_{av}, the vertical component of the force exerted by the shock absorber, and we may write immediately

$$\frac{d^2z}{dt^2} = \frac{M_s g - F_{av}}{M_s} \qquad \text{(Active Mode)}$$

The acceleration of the footpad, which is assumed to be massless, and the soil is determined by equating the soil force, which depends on the acceleration, with the force F_{av}. Solving for the acceleration, one finds

$$\frac{d^2 z_f}{dt^2} = \frac{F_{av} - F_i - \pi R^2 D\left(\frac{dz_f}{dt}\right)^2}{M_e}$$

where $\frac{d^2 z_f}{dt^2}$ is the acceleration of the footpad and soil slug.

The initial conditions appropriate to this problem are the spacecraft center of mass moving downward with a velocity V, and the footpad in contact with the surface but having zero velocity. Motion of the soil at the time of footpad contact would imply an infinite transient force to accelerate the soil. Just before footpad contact, the footpad has a downward velocity V, but the instantaneous deceleration is compatible with a massless footpad. A more realistic approximation may be to include footpad mass in the calculation and to define the footpad velocity immediately after contact with the surface by means of momentum conservation between the footpad and the slug of soil. No attempt has been made to carry out such calculations, but there is no reason to expect the final results are sensitive to the implementation of the initial conditions.

5.0 RESULTS

In this section the results of the simulations will be discussed. The comparison of these data with the results of Surveyor I are deferred until the next section.

The footpad penetration data for various soils, for both Surveyor and LM, are shown in Figures 9 through 18. The Surveyor crush block penetration data are shown in Figures 19 through 23.

In each figure the penetration is plotted as a function of cohesion of the soil for a fixed angle of internal friction and soil density. In order to compare Surveyor and LM in the same soil, it is necessary to choose the same parameters to describe the soil, that is, internal friction angle, density and cohesion. The static bearing capacity is not a property of the soil alone, but depends on the dimensions of the object which is penetrating the soil. The penetrations were plotted as a function of cohesion, and not bearing strength, so that the comparison could be made for the same soil. In the figures subsidiary scales show the surface static bearing capacity separately for Surveyor and for LM.

The parameters describing the spacecraft were chosen to correspond to the Surveyor I mission[5], on one hand, and to the nominal LM mission on the other. A list of the parameters used for Surveyor is given in Table IV, and for LM in Table V. For Surveyor the vertical impact velocity was taken to be 11.7 ft/sec, and for LM the vertical impact velocity was 10 ft/sec. The diameter of the Surveyor footpad is 8 inches. This corresponds to the diameter of the footpad at the bottom (see Figure 3). As the footpad penetrates the surface, more of the conical section comes into contact with the surface, and the cross sectional area of the soil slug should increase. This effect has been neglected, and for our purpose the Surveyor footpad is a right circular cylinder having a diameter of 8 inches.

The calculations for LM were run for two specific cases: (a) the spacecraft touches down equally on all four of its landing legs (LM, 4 leg), and (b) the entire landing maneuver takes place on a single leg (LM, 1 leg). The 1-legged LM landing is an improbable and extreme situation, while the 4-legged landing is an idealized perfect landing. In most circumstances it would be expected that one or two legs would strike the surface first, and that all four legs would eventually participate in the landing. For a given soil the 4-legged LM landing creates the least penetration possible, while the 1-legged landing gives the maximum.

The parameters which describe the soil have been varied over a wide range. The internal friction angle of the soil was varied from 0° to 40°. Two values of the soil density were considered: $\rho = 1$ slug/ft^3, corresponding to a very underdense surface, and $\rho = 3$ slugs/ft^3, a value typical of terrestrial soils. For each choice of the internal friction angle and density the cohesion was varied from zero to whatever value was required to give zero penetration.

From Figures 9 through 18 it may be seen that the behavior of the footpad penetration, as a function of the cohesion, is similar for all values of the internal friction and density. The characteristics of the curves depend on the relationship between the forces exerted by the shock absorber and the strength of the soil. These relationships are more easily understood as a function of the static bearing capacity of the soil. For a Surveyor footpad the penetration is a smooth curve which becomes tangent to zero penetration in the vicinity of 9 psi. The penetration goes to zero at a surface static bearing capacity of 9.83 psi. This is the maximum pressure that the Surveyor footpads expect on an unyielding surface when the touchdown velocity is 11.7 ft/sec, and clearly any soil with a static bearing capacity of 9.83 psi or greater appears impenetrable to the footpad. It is important to note, however, that the Surveyor crush blocks do penetrate the surface for soils having a static bearing capacity of up to 40 psi.

The behavior of the Surveyor crush block penetration is given in Figures 19 through 23. All of the curves are similar; they go sharply to zero at 40 psi and are relatively flat at about 0.1 foot penetration between 10 and 40 psi. Very little crushing (less than .01 foot) of the block occurs for bearing capacities less than 35 psi. For surfaces of 40 psi or greater static bearing capacity, the crush block does not penetrate but crushes .09 feet.

The maximum pressure which can be exerted by the LM corresponds to the maximum crush force of shock absorber honeycomb (see Figure 5). This value, which is independent of touchdown velocity, and which is the same for the 1-leg and 4-leg cases, is 9.33 psi. The penetration curve rises rapidly as the surface static bearing capacity decreases below this value. The penetration for the 4-leg case has a plateau between 5 and 9 psi, roughly. At levels below 4 psi the penetration rises more sharply with decreasing soil strength because for soils of such strength the shock absorber does not stroke at all and the entire deceleration of the spacecraft occurs due to penetration of the footpad into the surface. For soils with a surface static bearing capacity above 4.42 psi, the entire length of the weaker honeycomb must crush before any penetration into the surface can occur.

The most striking result which can be seen is that the penetration of an LM landing of 4-legs is quite similar to that of a Surveyor footpad. The case of a 1-legged LM landing gives penetrations which are too great to be of interest for this study.

6.0 COMPARISON WITH SURVEYOR I

The purpose of this section is to compare the penetration data of Surveyor I with the results of the simulation, and, in terms of the soil model, to determine the parameters which describe the lunar material. In addition, the results for an LM landing in the same material are developed.

In this study the only Surveyor I data which are used directly are the penetration of the footpads and crush block into the surface. Data from the strain gages have been used elsewhere to deduce information about the lunar surface.[6]

In addition, television pictures of the lunar material surrounding the Surveyor footpads provide an indication of the nature of the lunar soil. These data indicate that the lunar surface is composed of a granular material with a small amount of cohesion, a material qualitatively similar to a "terrestrial, damp, fine-grained soil."[1] It is important to note that this description is consistent with the incompressible soil model on which this study is based. It is not correct to assume that the soil model used here faithfully represents the behavior of the lunar material, but, based on the Surveyor television pictures, it is a reasonable model.

The penetration of the Surveyor footpads and crush blocks has been determined by studying shadows cast on the lunar surface. The measurements are difficult to interpret because it is not known if the footpad now lies at its level of deepest penetration during the actual landing, and because the disturbed material around the footpad obscures the original level of the surface. In the case of the crush block the measurement is further complicated by limited visibility. Consequently, the penetrations are not accurately known.

The reported penetrations[6] are 1-1/2 to 3 inches for leg 2, more than 1-1/4 inches for leg 3, and more than 3/4 inches for crush block 2; these are the only visible portions of the spacecraft which contacted the lunar surface. Because of the uncertainty in these measurements, it is convenient for our purposes to take the penetration of Surveyor footpads to be 3 inches (0.25 feet).

Table VI shows the soil parameters and the LM penetrations which correspond to a Surveyor footpad penetration of 0.25 feet. Several conclusions may be drawn from examination of these data.

The surface static bearing capacity required to produce a 0.25 foot penetration for the Surveyor footpad is about 6 psi, independent of the detailed characteristics of the soil. Second, the Surveyor crush block penetration is 0.4 feet independent of the soil characteristics. Third, the LM footpad penetration would be 0.4 feet for all except the soils with high internal friction angles. For these soils the penetration is less.

The Surveyor crush block penetration, 0.4 feet (about five inches), is greater than would be expected from Surveyor I pictures, although the only claim made is that the penetration is greater than 3/4 inch.[6] However, the measurement of the crush block penetration is difficult and uncertain, so that it cannot be determined if the results of the simulation disagree with data from Surveyor I. A significant disagreement would, of course, cast doubt on the reliability of the simulation or on the soil model which has been used in this study.

On the basis of penetration data there is no way to choose between the sets of soil parameters which yield the desired Surveyor footpad penetration. The only conclusion that can be drawn is that a surface static bearing capacity of 6 psi is required.

This estimate of the soil static bearing capacity does not disagree with the estimate made by the Surveyor Scientific Evaluation and Analysis Team(1), who estimated that a static bearing capacity of about 5 psi was required. This estimate was derived from a landing dynamics analysis which is similar to the present simulation, but which used a simpler model for the Surveyor spacecraft. Based on the appearance of the distrubed soil around the footpads, they further estimate a reasonable choice is an internal friction angle between 30° and 40°, a density of 3 slugs/ft^3 and a cohesion between 0.02 and 0.05 psi.

In addition, it may be seen from Table VI that for those soil parameters which give 0.25 feet Surveyor footpad penetration the expected LM 4-legged penetration is 0.4 feet for low friction angle materials and decreases for higher friction angles. Although on the basis of Surveyor I penetration data alone it is not possible to distinguish between soils having a wide range of characteristics, these soils do not vary widely in the predicted LM penetration; that is, we can more reliably state that the expected LM penetration at the Surveyor I site is less than 0.4 feet than we can determine the detailed characteristics of the soil.

For any set of soil parameters which produced a Surveyor penetration of 0.25 feet, the 1-legged LM penetration exceeded 3.5 feet. These results are not reported in detail here.

The curves of the Surveyor footpad penetration versus static bearing capacity are relatively flat. The implication of this is that the penetration of the spacecraft is not a sensitive function of the static bearing capacity in the range of interest. Consequently, it is not possible to obtain an accurate estimate of the static bearing capacity of the soil, especially in view of the uncertainty in the Surveyor footpad penetration.

However, the curves of LM penetration versus static bearing capacity are also flat and closely parallel the corresponding curves for Surveyor. Because of this, it is possible to predict the LM penetration with essentially the same accuracy as the Surveyor penetration is known, except for the limitations of the simulation procedure itself.

Finally, it has been noted that all of the simulations were run at a Surveyor touchdown velocity of 11.7 ft/sec. The touchdown velocity for future Surveyor missions may differ from this value because of the inherent uncertainties in the guidance system. An indication of the sensitivity of the landing dynamics simulation to the touchdown velocity is given in Table VII, which, for a soil having an internal friction angle of 30°, gives the footpad penetration for various touchdown velocities.

7.0 CONCLUSIONS

It must be understood that the conclusions which are reached in this report are subject to the limitations imposed by the assumptions which were made in developing the computer simulation program. These limitations are the restriction to a single soil model, which, though consistent with lunar television observations, is of undetermined validity on the moon, and the one-dimensional character of the simulation program and the soil model which ignore lateral motion of the footpads and soil. Within these limitations we may conclude that:

1. the static bearing capacity on the lunar surface, in the vicinity of Surveyor I, is about 6 psi;

2. the Surveyor crush blocks penetrated the surface 0.4 feet;

3. if LM lands evenly on all 4 legs at the Surveyor I site, a maximum penetration of 0.4 feet would occur; and

4. a penetration of greater than 3.5 feet would be expected if the entire LM landing deceleration occurred with a single footpad in contact with the surface.

A more general conclusion is that the Surveyor penetration approximates the LM 4-legged penetration. This statement applies for a nominal LM landing of 10 ft/sec and a Surveyor touchdown velocity of 11.7 ft/sec.

E. N. Shipley

1014-ENS-jdc

Attachments
Tables I - VII
Figures 1 - 23

REFERENCES

1. L. D. Jaffe et al., "Surveyor I: Preliminary Results," Science 152, 1737 (1966).

2. Three dimensional Surveyor landing dynamics programs have been developed by R. Jones, Hughes Aircraft Company, and F. Sperling, Jet Propulsion Laboratory.

3. P. L. Chandeysson, Bellcomm Memorandum for File, December 7, 1966.

4. R. F. Scott, unpublished reports to Space General, Inc., October 26, 1962, November 5, 1962 and November 9, 1962.

5. Surveyor I Mission Report, Part I, Mission Description and Performance, Jet Propulsion Laboratory Technical Report No. 32-1023, August 13, 1966.

6. Surveyor I Mission Report, Part II, Scientific Data and Results, Jet Propulsion Laboratory Technical Report No. 32-1023, September 10, 1966.

INTERNAL FRICTION ANGLE, Φ

	0°	10°	20°	30°	40°
N_q	1	2.8	8	25	85
N_γ	0	0.8	5.5	26	140
N_c	5.14	9	16	40	100

TABLE I

SOIL PARAMETERS USED IN THIS STUDY. THE RELATIONSHIP BETWEEN THESE CONSTANTS AND THE SOIL FORCES IS GIVEN IN THE TEXT. THESE VALUES WERE OBTAINED FROM REFERENCE 3.

Φ	ρ = 1 slug/ft^3	ρ = 3 slugs/ft^3
0°	.04 psi/foot	.11 psi/foot
10°	.10 "	.31 "
20°	.30 "	.89 "
30°	.92 "	2.8 "
40°	3.1 "	9.4 "

TABLE II

RATE OF INCREASE OF THE STATIC BEARING CAPACITY WITH PENETRATION INTO THE LUNAR SURFACE. THE UNITS ARE PSI PER FOOT OF PENETRATION. Φ IS THE INTERNAL FRICTION ANGLE OF THE SOIL.

		C, slugs/ft^2	D, slugs/ft^3
LM	ρ = 1 slug/ft^3	1.25	.14
	ρ = 3 "	3.75	.42
Surveyor Footpad	ρ = 1 "	.28	.14
	ρ = 3 "	.83	.42
Surveyor Crush Block	ρ = 1 "	.24	.14
	ρ = 3 "	.71	.42

TABLE III

C, THE EFFECTIVE MASS AT THE SURFACE, AND D, THE RATE OF INCREASE OF EFFECTIVE MASS WITH PENETRATION. BOTH QUANTITIES REFER TO A UNIT FOOTPAD AREA. THESE QUANTITIES GIVE RISE TO THE DYNAMIC FORCES IN THE SOIL

Surveyor mass (at touchdown)	20.0	slugs
Touchdown velocity	11.7	ft/sec.
Shock Absorber		
Preload force	180	pounds
Spring constant	280	pounds/inch
Damping function	see Figure 4	
Crush Block		
Crushing pressure	40.	psi
Radius	.34	feet
Footpad		
Radius	.33	feet

TABLE IV

SURVEYOR PARAMETERS USED IN THE SIMULATION.

LM mass	500.	slugs
Touchdown velocity	10.	ft./sec.
Shock Absorber		
Crushing function	see Figure 5	
Footpad		
Radius	1.5	feet

TABLE V

LM PARAMETERS USED IN THE SIMULATION.

SURVEYOR FOOTPAD PENETRATION = 0.25 FEET

SOIL PARAMETERS			SURVEYOR FOOTPAD	SURVEYOR CRUSH BLOCK	LM
INTERNAL FRICTION	DENSITY	COHESION	SURFACE STATIC BEARING CAPACITY	PENETRATION	PENETRATION (4 LEGS)
0°	1 slug/ft^3	.95 psi	6.3 psi	0.39 ft	.42 ft
0°	3	.95	6.3	0.36	.31
10°	1	.55	6.4	.38	.40
10°	3	.54	6.4	.37	.42
20°	1	.30	6.3	.40	.42
20°	3	.30	6.3	.38	.27
30°	1	.12	6.2	.40	.36
30°	3	.11	6.1	.38	.14
40°	1	.038	5.9	.40	0.
40°	3	.015	5.1	.40	0.

TABLE VI

SURFACE STATIC BEARING CAPACITY FOR SURVEYOR AND LM FOOTPAD PENETRATION FOR COMBINATIONS OF SOIL PARAMETERS WHICH GIVE A SURVEYOR FOOTPAD PENETRATION OF 0.25 FEET.

$\phi = 30°$

	ρ = 1 slug/ft^3 c = .04 psi A = 2.27 psi	ρ = 3 slugs/ft^3 c = .04 psi A = 2.66 psi	ρ = 1 slug/ft^3 c = .12 psi A = 6.43 psi	ρ = 3 slugs/ft^3 c = .12 psi A = 6.82 psi
V = 4 ft/sec	.38 ft	.19 ft	0 ft	0 ft
6	.76	.43	0	0
8	1.11	.63	0	0
10	1.51	.83	.074	.038
11.7	1.86	1.01	.22	.14
12	1.92	1.04	.25	.16
14	2.36	1.27	.48	.33
16	——	1.49	.75	.53
18	——	1.73	1.05	.73
20	——	——	1.37	.95

TABLE VII

SURVEYOR FOOTPAD PENETRATION AS A FUNCTION OF THE TOUCHDOWN VELOCITY V. THE INTERNAL FRICTION ANGLE OF THE SOIL IS 30°. ρ IS THE DENSITY OF THE SOIL, C IS THE COHESION, AND A IS THE STATIC BEARING CAPACITY AT THE SURFACE FOR A SURVEYOR FOOTPAD.

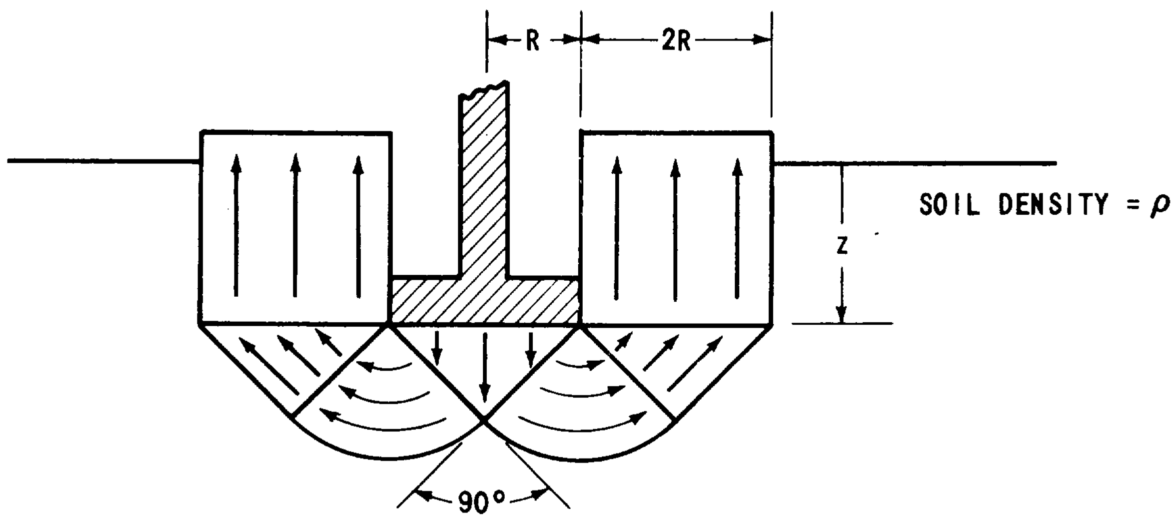


FIGURE 1 - FLOW PATTERN FOR INCOMPRESSIBLE MODEL SOIL (FROM REFERENCE 3)

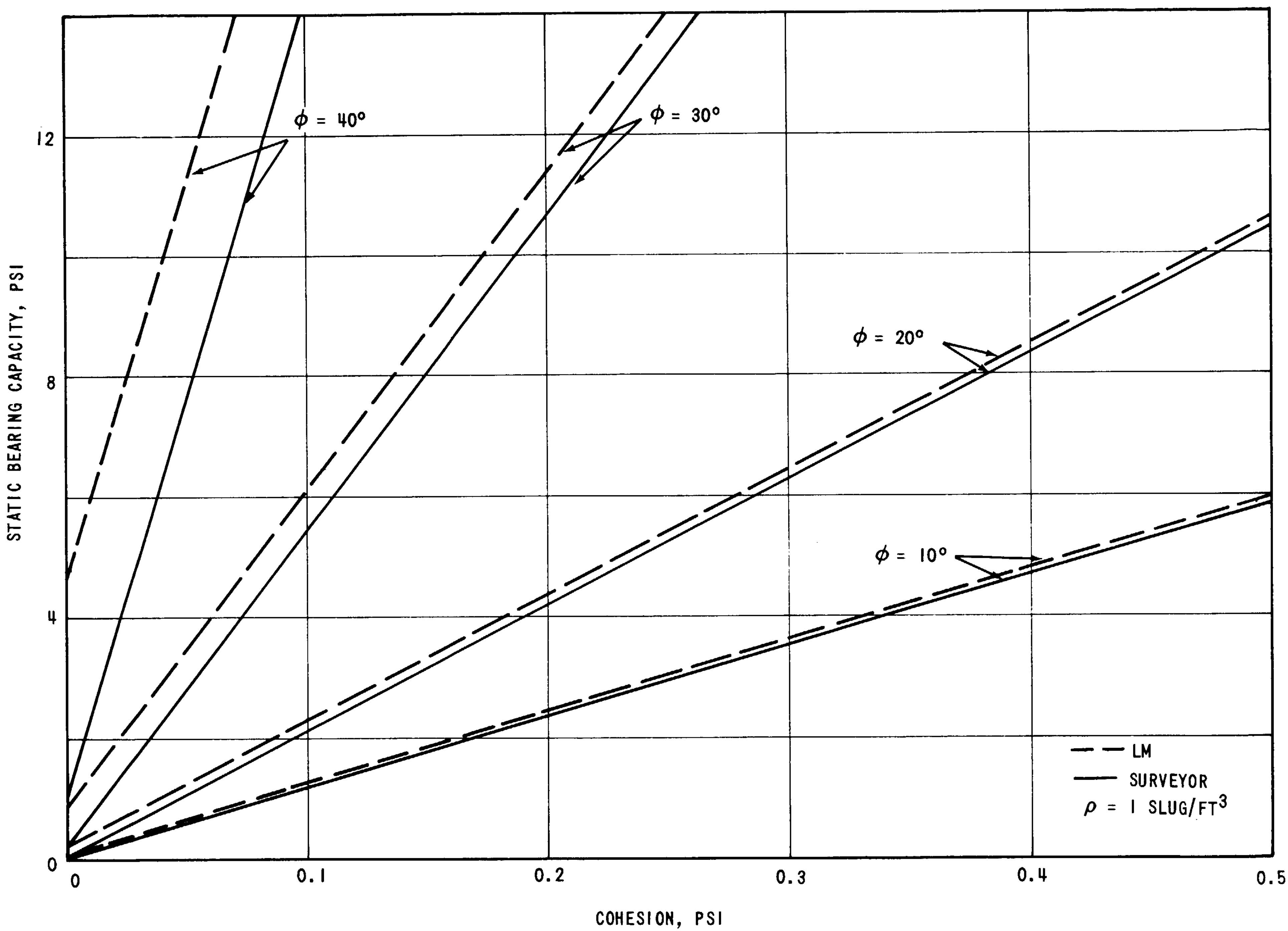
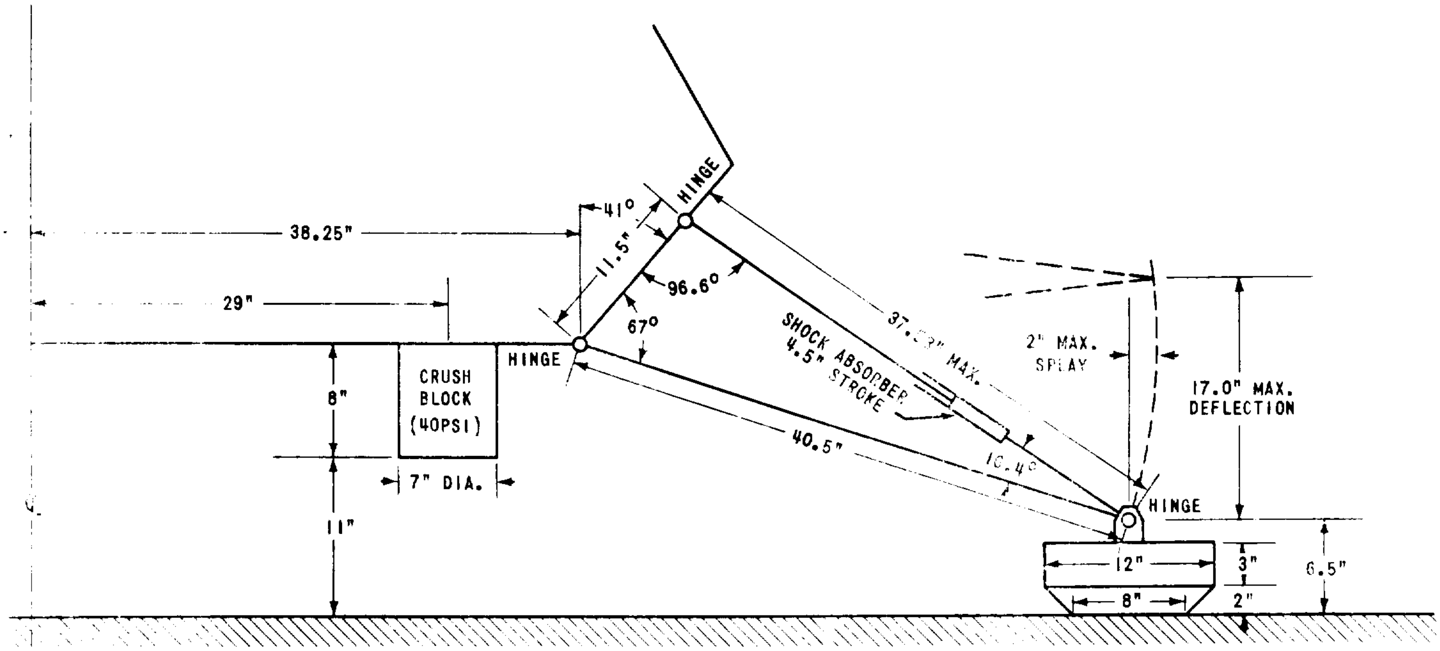


FIGURE 2 - STATIC BEARING CAPACITY AT THE LUNAR SURFACE



FOOTPAD DETAIL

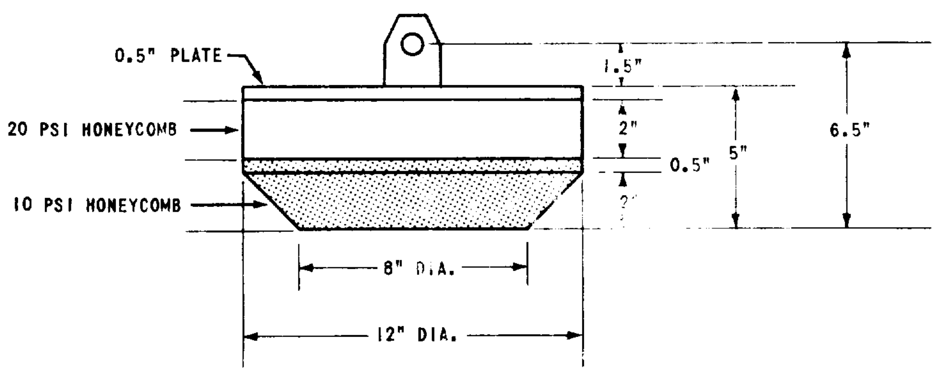


FIGURE 3 - SURVEYOR SHOCK ABSORBER GEOMETRY

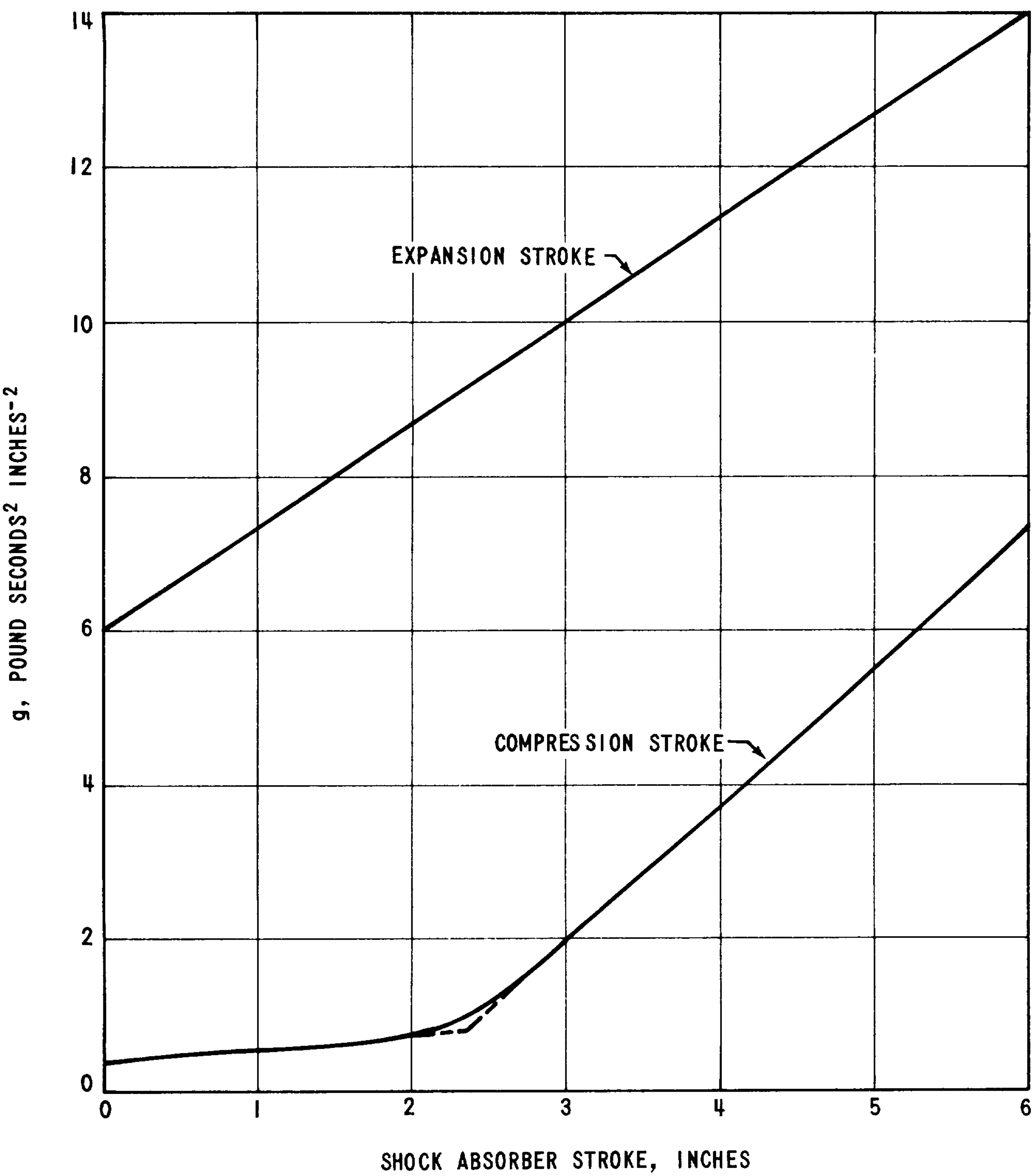


FIGURE 4 - REPRESENTATIVE SURVEYOR SHOCK ABSORBER DAMPING FUNCTION. THE VALUES USED IN THE SIMULATION PROGRAM DEVIATE FROM THE REPRESENTATIVE FUNCTION AS SHOWN BY THE DOTTED LINE.

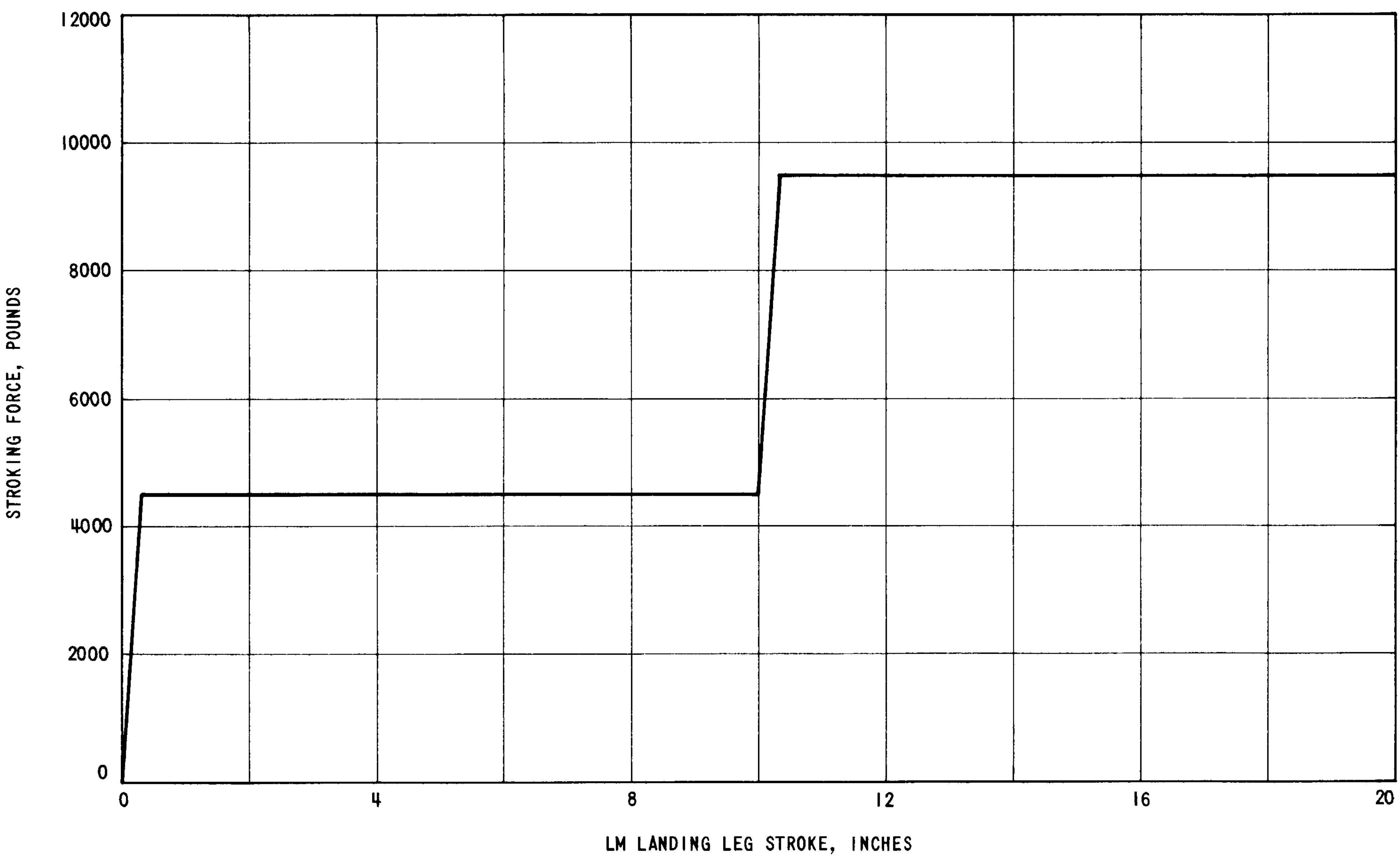


FIGURE 5 - FORCE REQUIRED TO CAUSE STROKING OF THE LM SHOCK ABSORBER

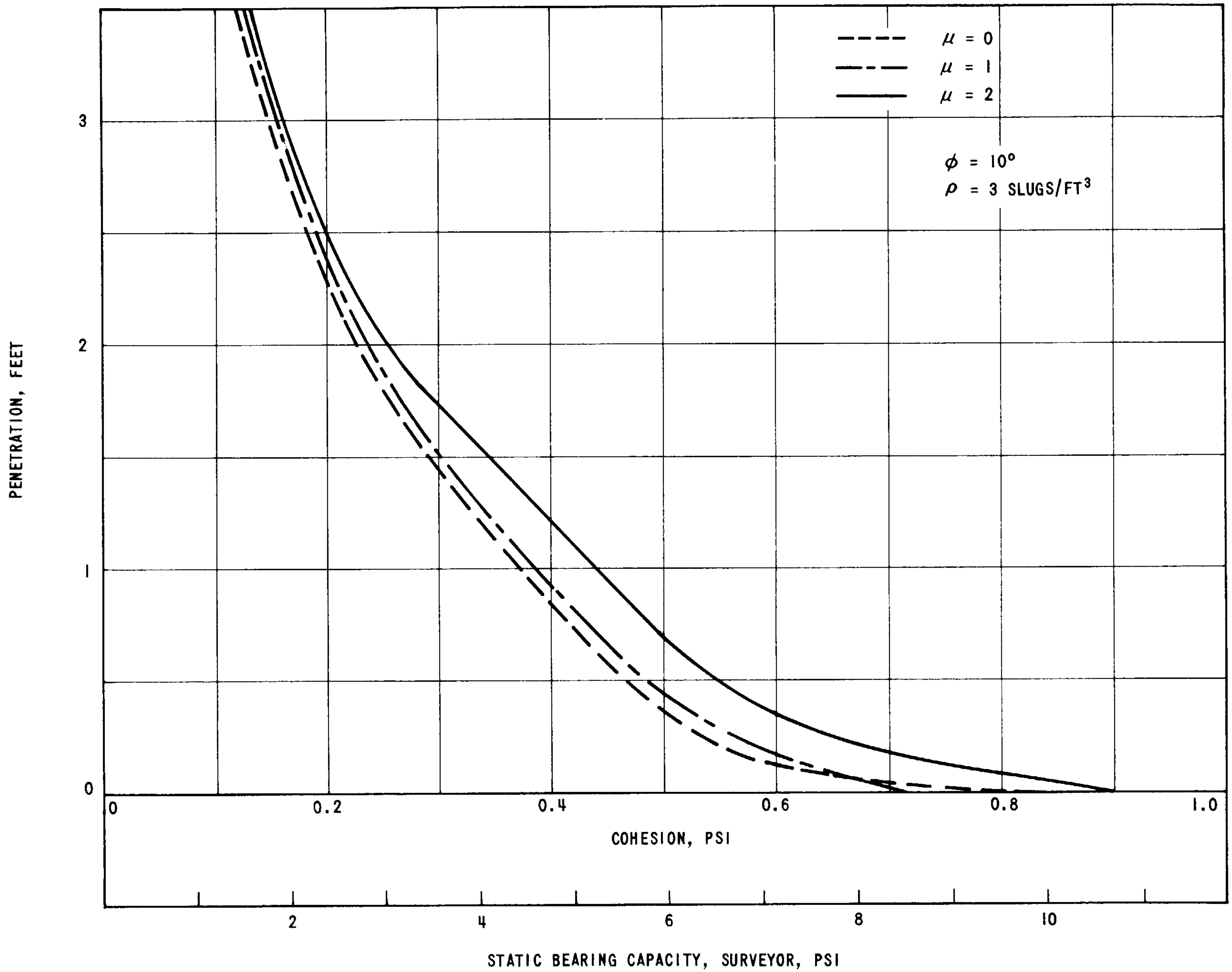


FIGURE 6 - EFFECT OF FRICTION ON THE PENETRATION OF A SURVEYOR FOOTPAD INTO THE MODEL LUNAR SOIL. THE PARAMETER μ IS THE COEFFICIENT OF FRICTION. CONSTANTS USED IN THE SIMULATION ARE GIVEN IN TABLE IV.

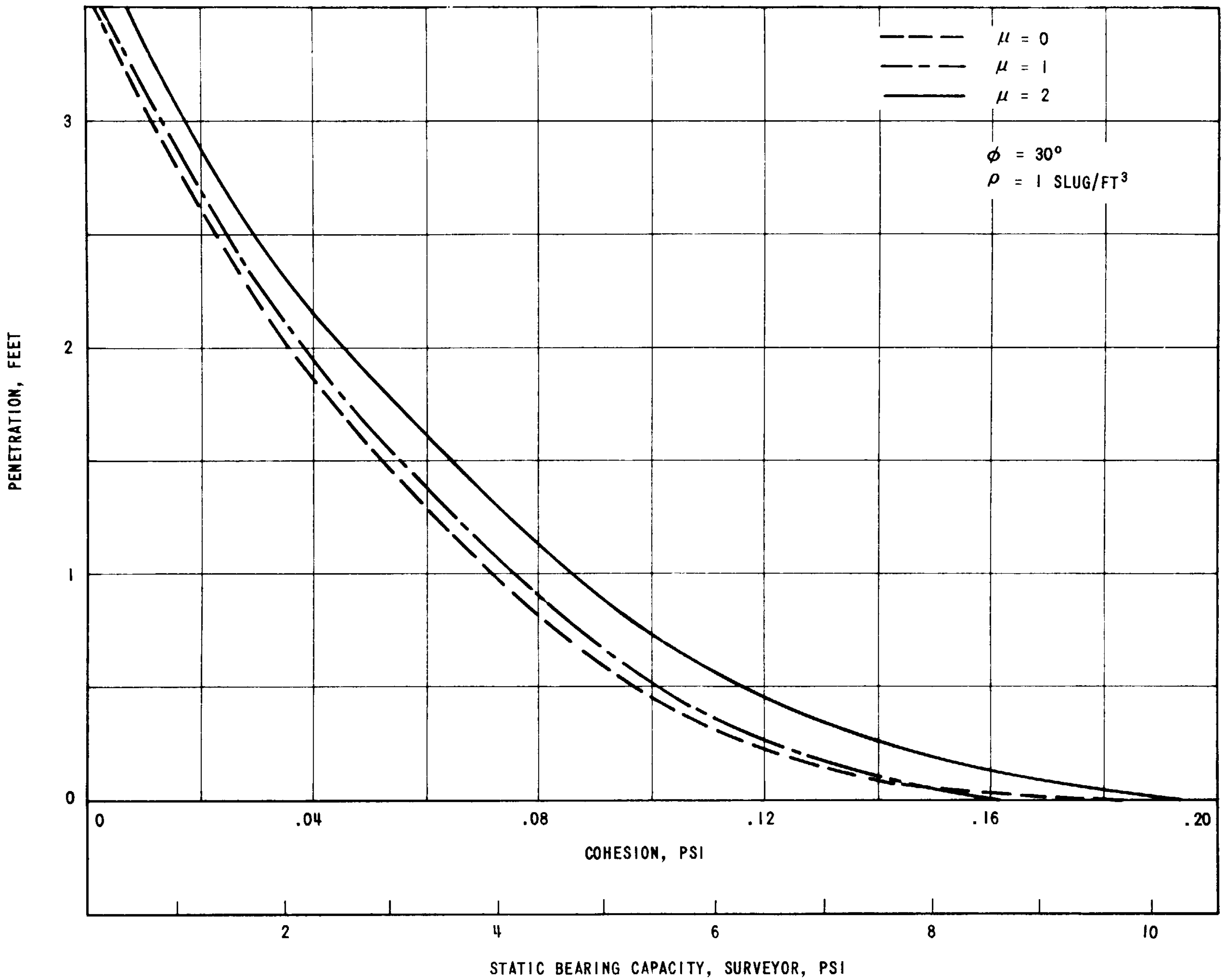


FIGURE 7 - EFFECT OF FRICTION ON THE PENETRATION OF A SURVEYOR FOOTPAD INTO THE MODEL LUNAR SOIL. THE PARAMETER μ IS THE COEFFICIENT OF FRICTION. CONSTANTS USED IN THE SIMULATION ARE GIVEN IN TABLE IV.

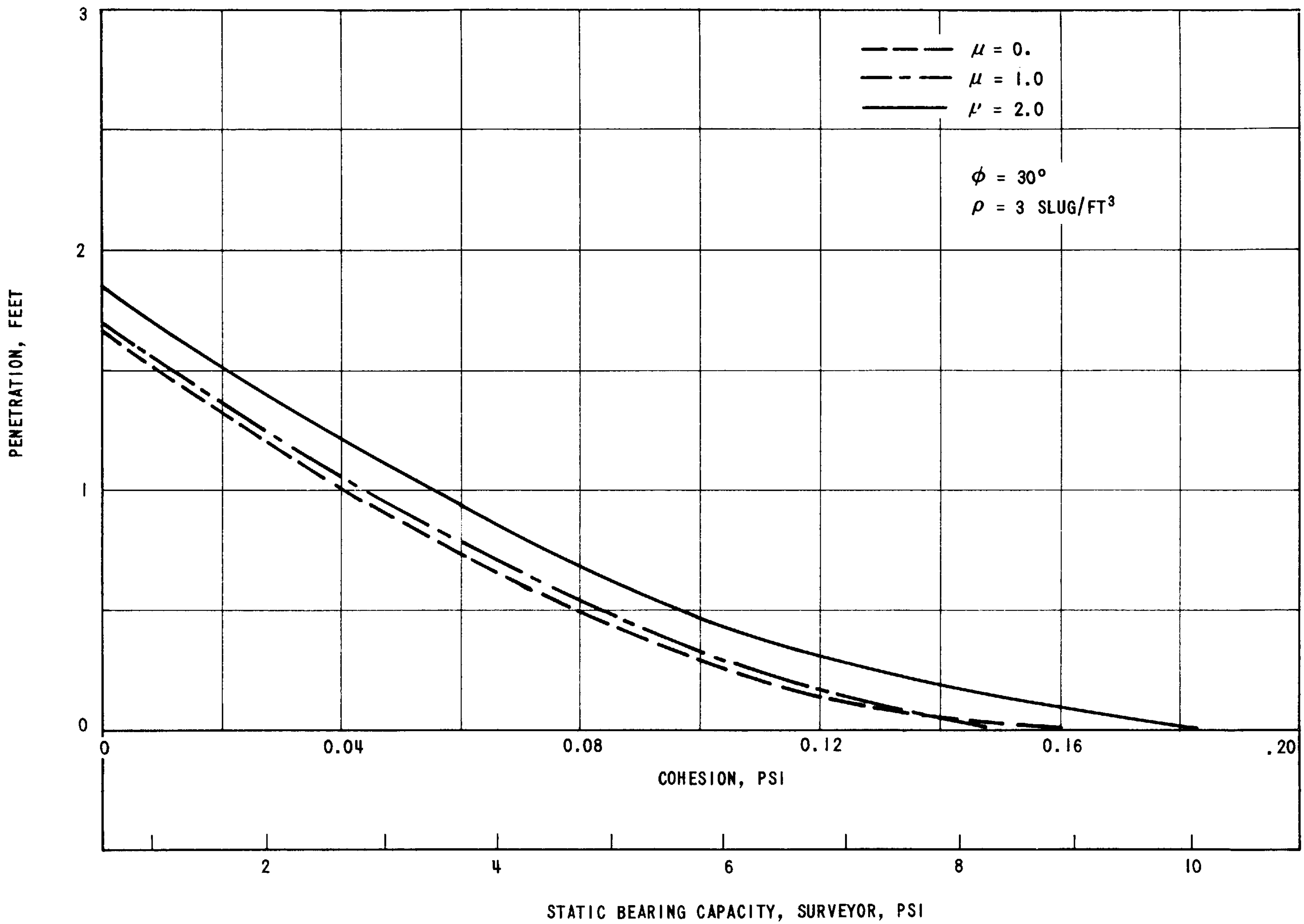


FIGURE 8 - EFFECT OF FRICTION ON THE PENETRATION OF A SURVEYOR FOOTPAD INTO THE MODEL LUNAR SOIL. THE PARAMETER μ IS THE COEFFICIENT OF FRICTION. CONSTANTS USED IN THE SIMULATION ARE GIVEN IN TABLE IV.

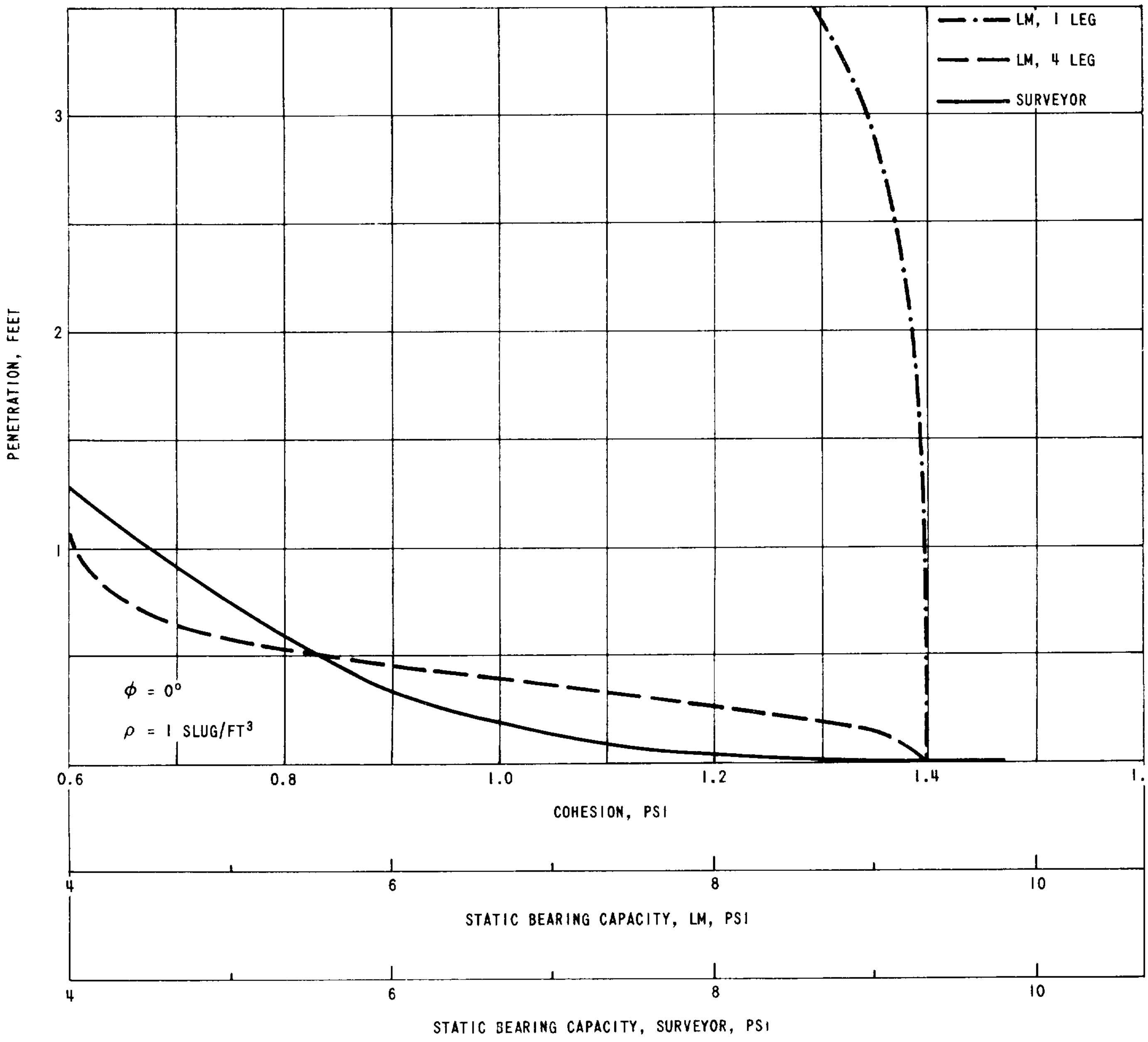


FIGURE 9 - PENETRATION OF SURVEYOR AND LM FOOTPADS INTO THE MODEL LUNAR SOIL. ϕ IS THE INTERNAL FRICTION ANGLE AND ρ IS THE DENSITY OF THE SOIL. THE BEARING CAPACITY SCALES REFER TO THE SPACECRAFT FOOTPADS AT ZERO PENETRATION.

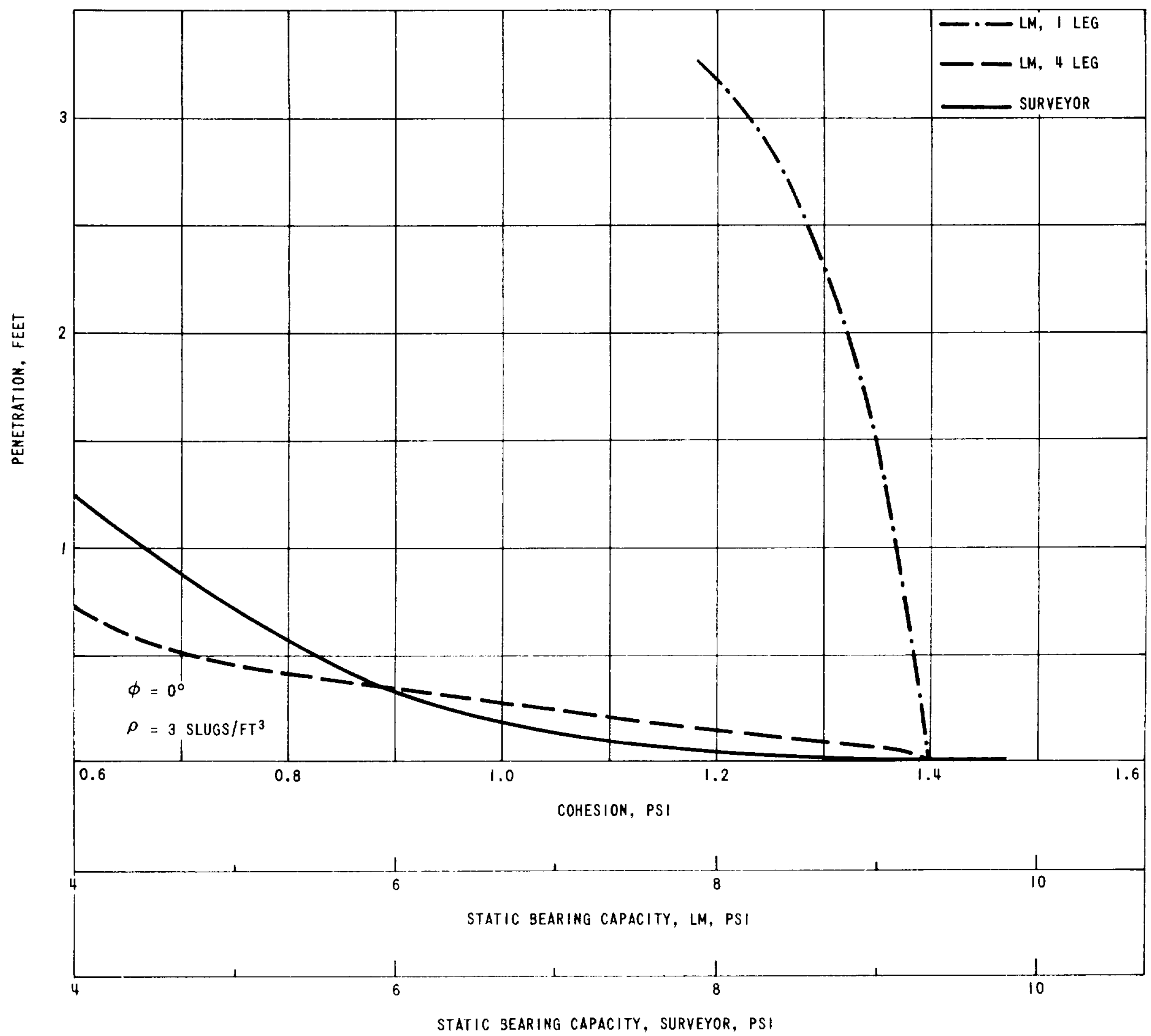


FIGURE 10 - PENETRATION OF SURVEYOR AND LM FOOTPADS INTO THE MODEL LUNAR SOIL. ϕ IS THE INTERNAL FRICTION ANGLE AND ρ IS THE DENSITY OF THE SOIL. THE BEARING CAPACITY SCALES REFER TO THE SPACECRAFT FOOTPADS AT ZERO PENETRATION.

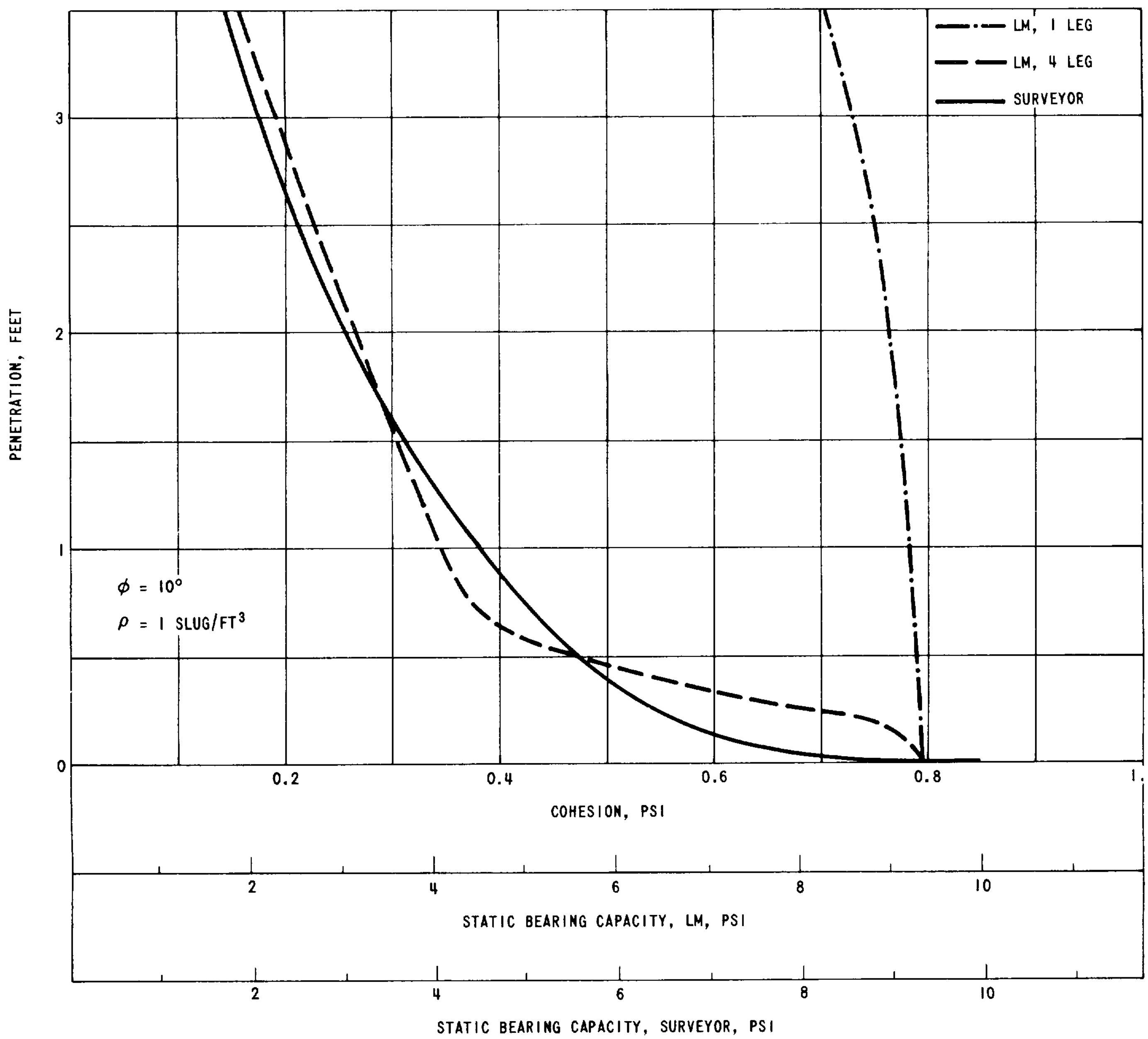


FIGURE 11 - PENETRATION OF SURVEYOR AND LM FOOTPADS INTO THE MODEL LUNAR SOIL. ϕ IS THE INTERNAL FRICTION ANGLE AND ρ IS THE DENSITY OF THE SOIL. THE BEARING CAPACITY SCALES REFER TO THE SPACECRAFT FOOTPADS AT ZERO PENETRATION.

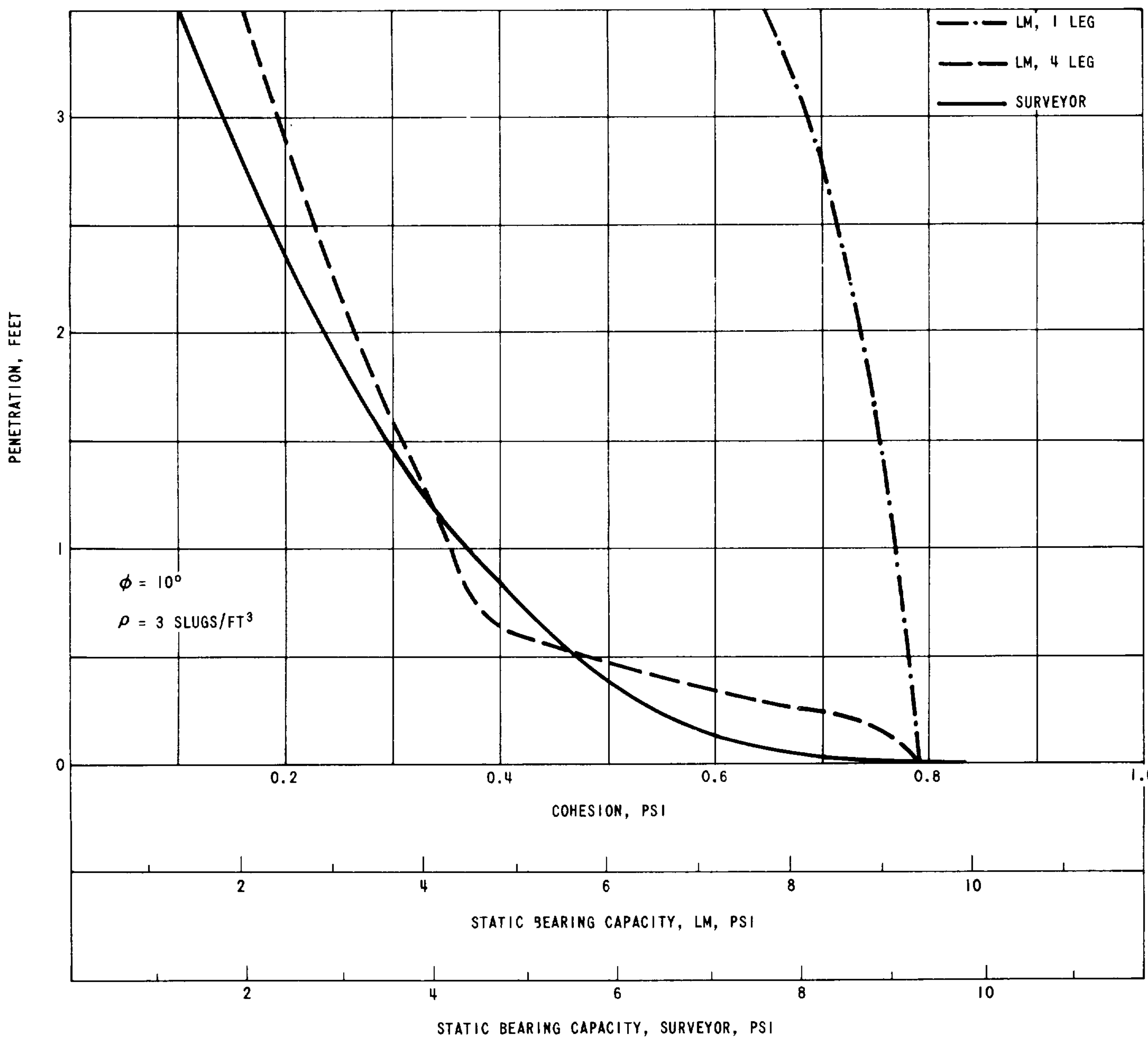


FIGURE 12 - PENETRATION OF SURVEYOR AND LM FOOTPADS INTO THE MODEL LUNAR SOIL. ϕ IS THE INTERNAL FRICTION ANGLE AND ρ IS THE DENSITY OF THE SOIL. THE BEARING CAPACITY SCALES REFER TO THE SPACECRAFT FOOTPADS AT ZERO PENETRATION.

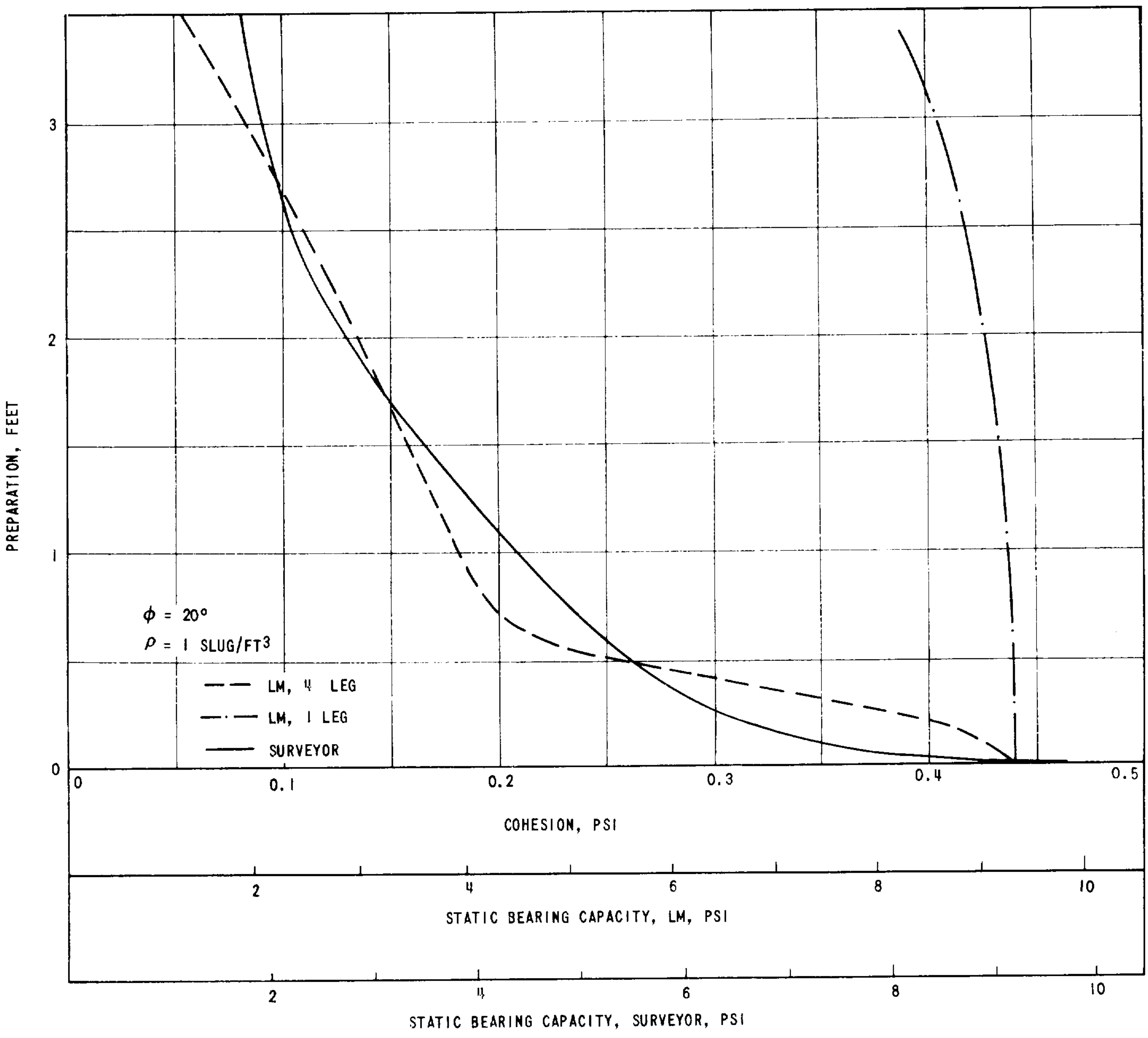


FIGURE 13 - PENETRATION OF SURVEYOR AND LM FOOTPADS INTO THE MODEL LUNAR SOIL. ϕ IS THE INTERNAL FRICTION ANGLE AND ρ IS THE DENSITY OF THE SOIL. THE BEARING CAPACITY SCALES REFER TO THE SPACECRAFT FOOTPADS AT ZERO PENETRATION.

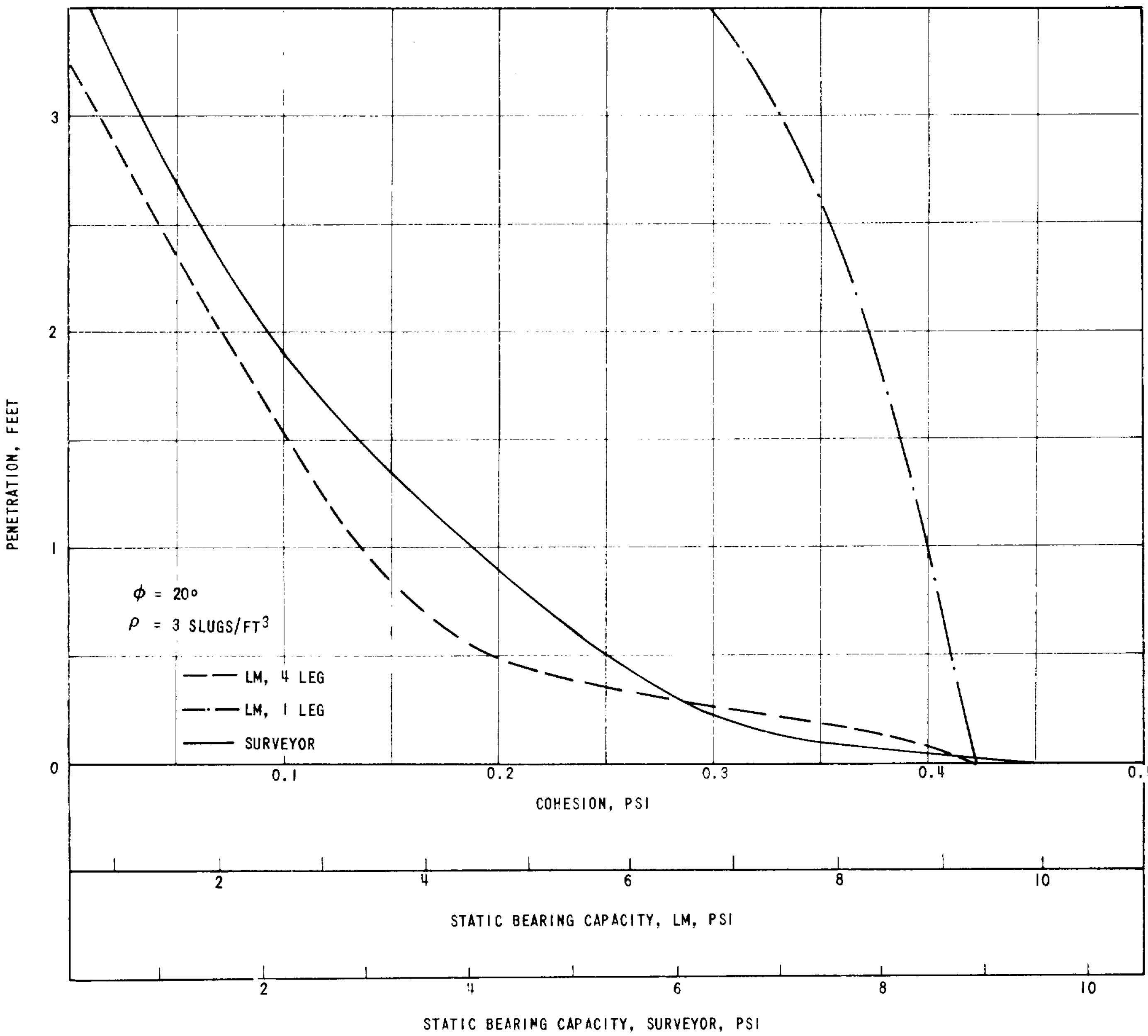


FIGURE 14 - PENETRATION OF SURVEYOR AND LM FOOTPADS INTO THE MODEL LUNAR SOIL. ϕ IS THE INTERNAL FRICTION ANGLE AND ρ IS THE DENSITY OF THE SOIL. THE BEARING CAPACITY SCALES REFER TO THE SPACECRAFT FOOTPADS AT ZERO PENETRATION.

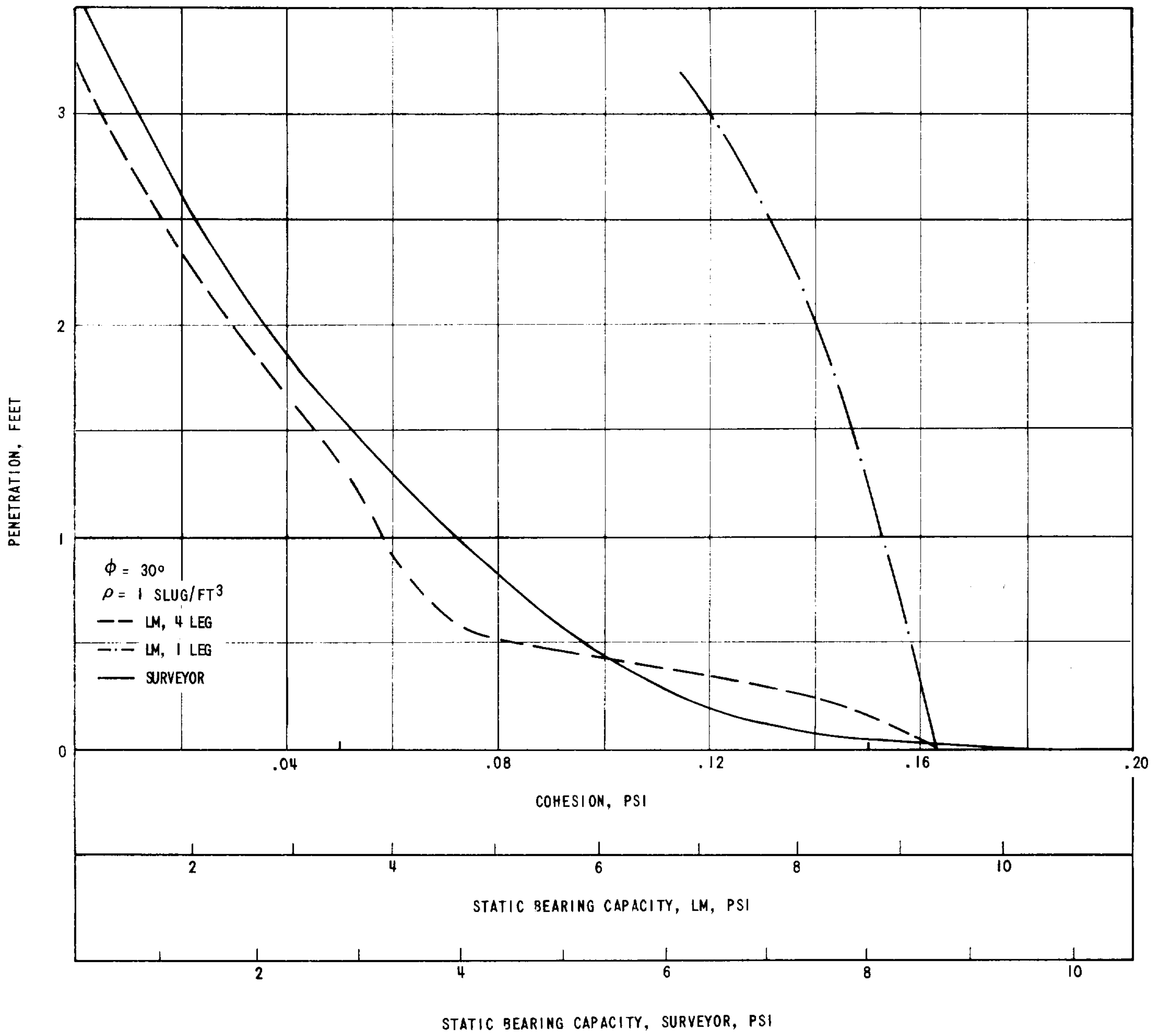


FIGURE 15 - PENETRATION OF SURVEYOR AND LM FOOTPADS INTO THE MODEL LUNAR SOIL. ϕ IS THE INTERNAL FRICTION ANGLE AND ρ IS THE DENSITY OF THE SOIL. THE BEARING CAPACITY SCALES REFER TO THE SPACECRAFT FOOTPADS AT ZERO PENETRATION.

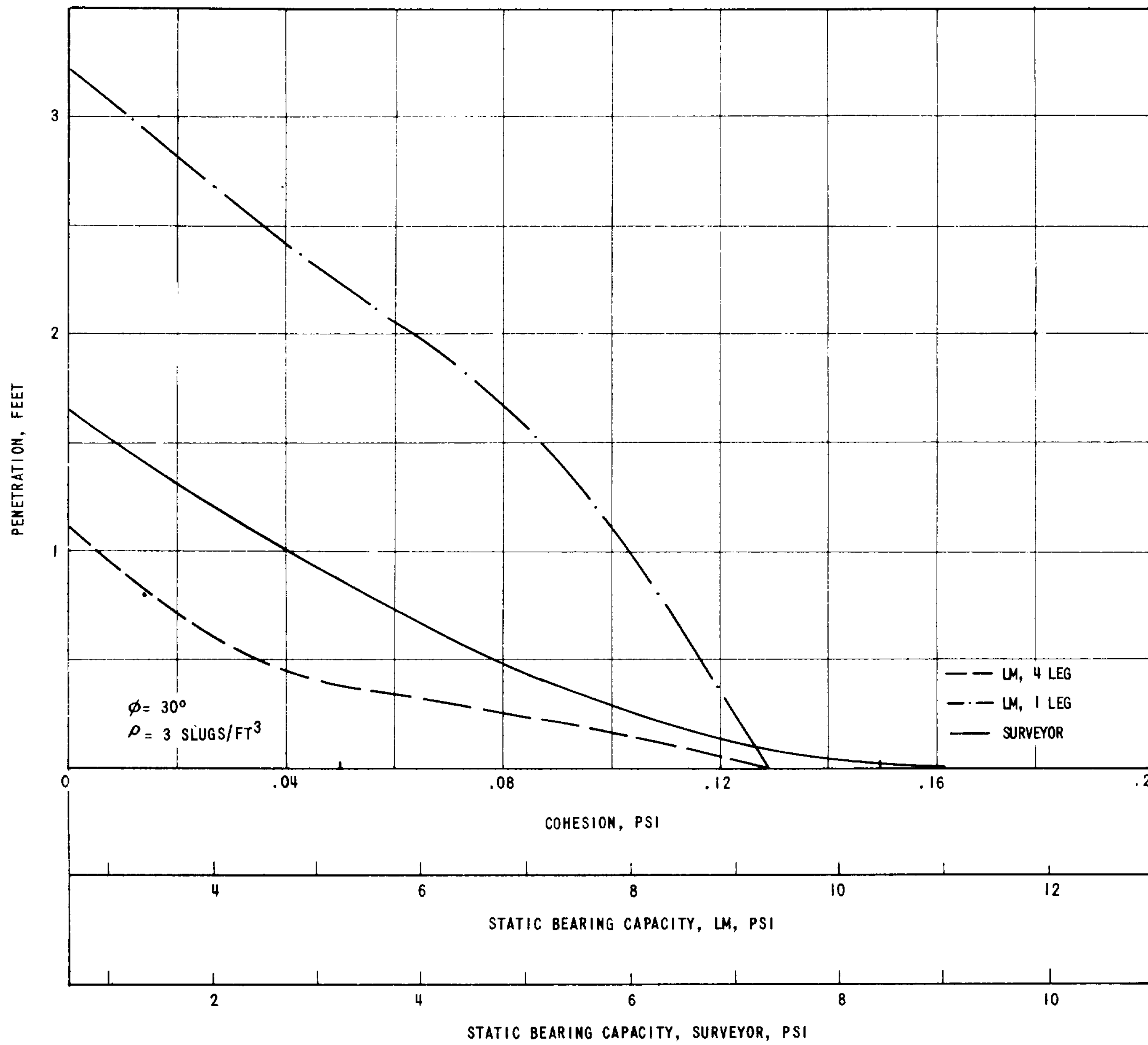


FIGURE 16 - PENETRATION OF SURVEYOR AND LM FOOTPADS INTO THE MODEL LUNAR SOIL. ϕ IS THE INTERNAL FRICTION ANGLE AND ρ IS THE DENSITY OF THE SOIL. THE BEARING CAPACITY SCALES REFER TO THE SPACECRAFT FOOTPADS AT ZERO PENETRATION.

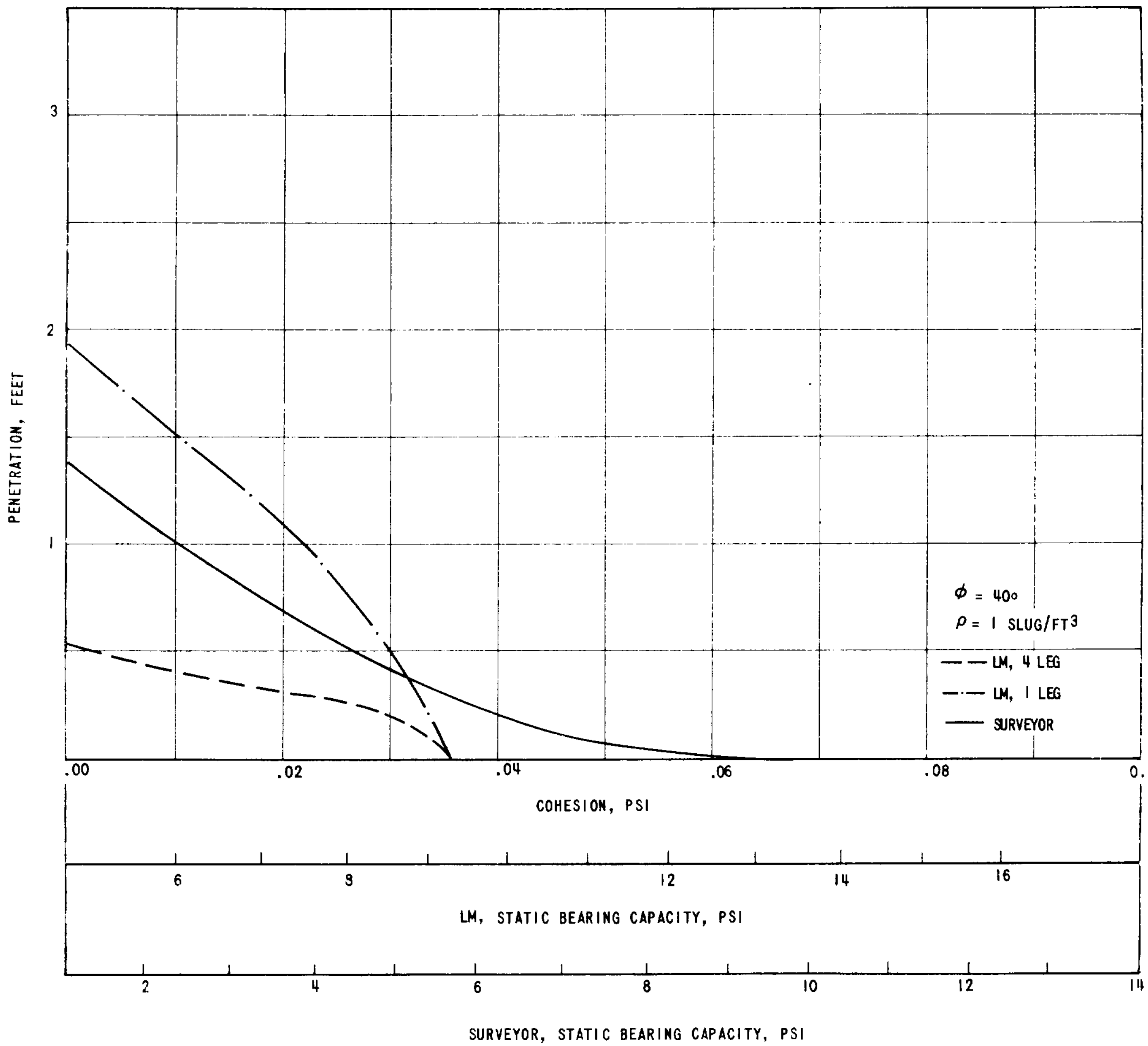


FIGURE 17 - PENETRATION OF SURVEYOR AND LM FOOTPADS INTO THE MODEL LUNAR SOIL. ϕ IS THE INTERNAL FRICTION ANGLE AND ρ IS THE DENSITY OF THE SOIL. THE BEARING CAPACITY SCALES REFER TO THE SPACECRAFT FOOTPADS AT ZERO PENETRATION.

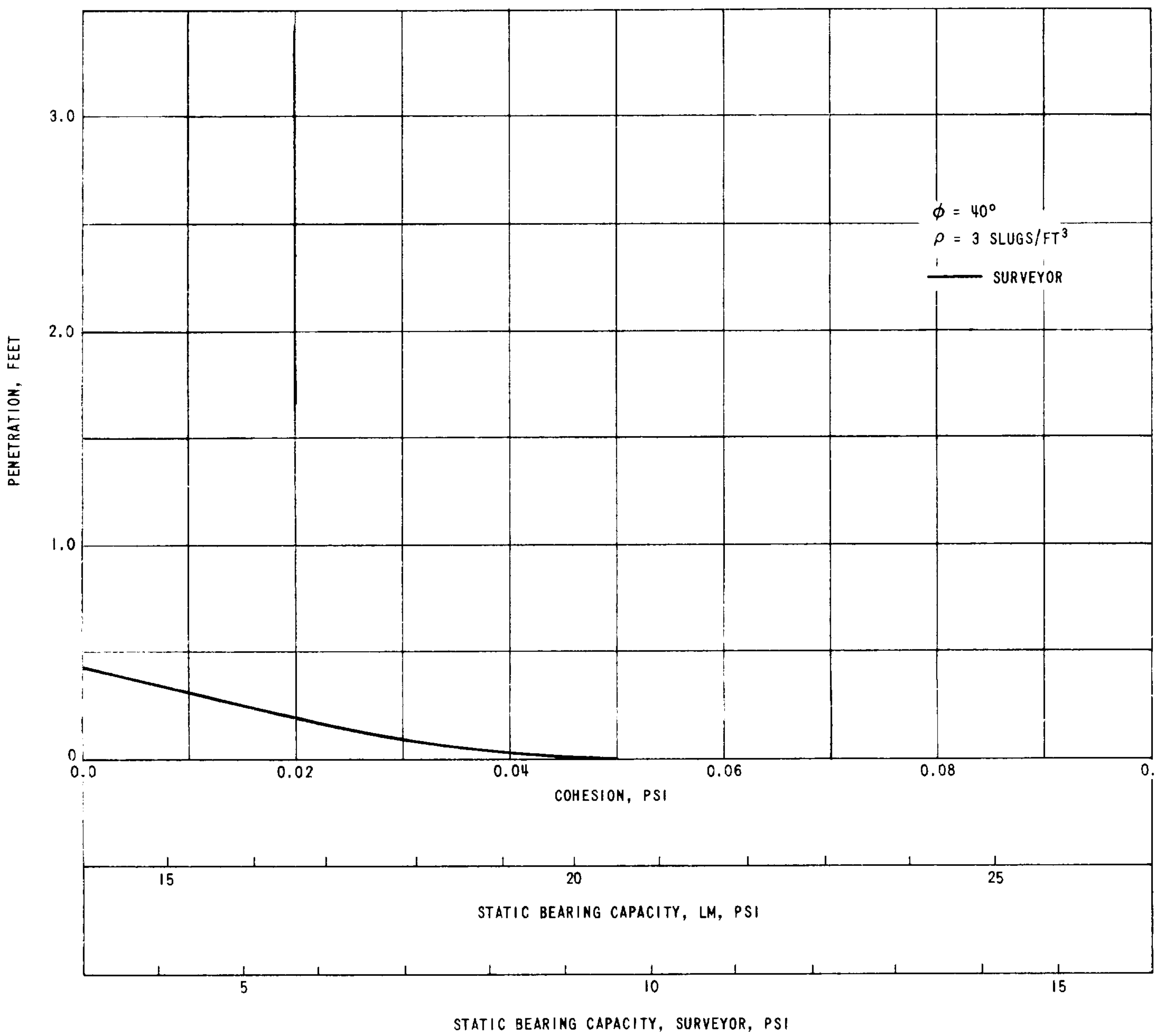


FIGURE 18 - PENETRATION OF A SURVEYOR FOOTPAD INTO THE MODEL LUNAR SOIL. ϕ IS THE INTERNAL FRICTION ANGLE AND ρ IS THE DENSITY OF THE SOIL. THE LM PENETRATION IS ZERO FOR ALL POINTS BECAUSE OF THE HIGH BEARING CAPACITY FOR THE LM FOOTPAD.

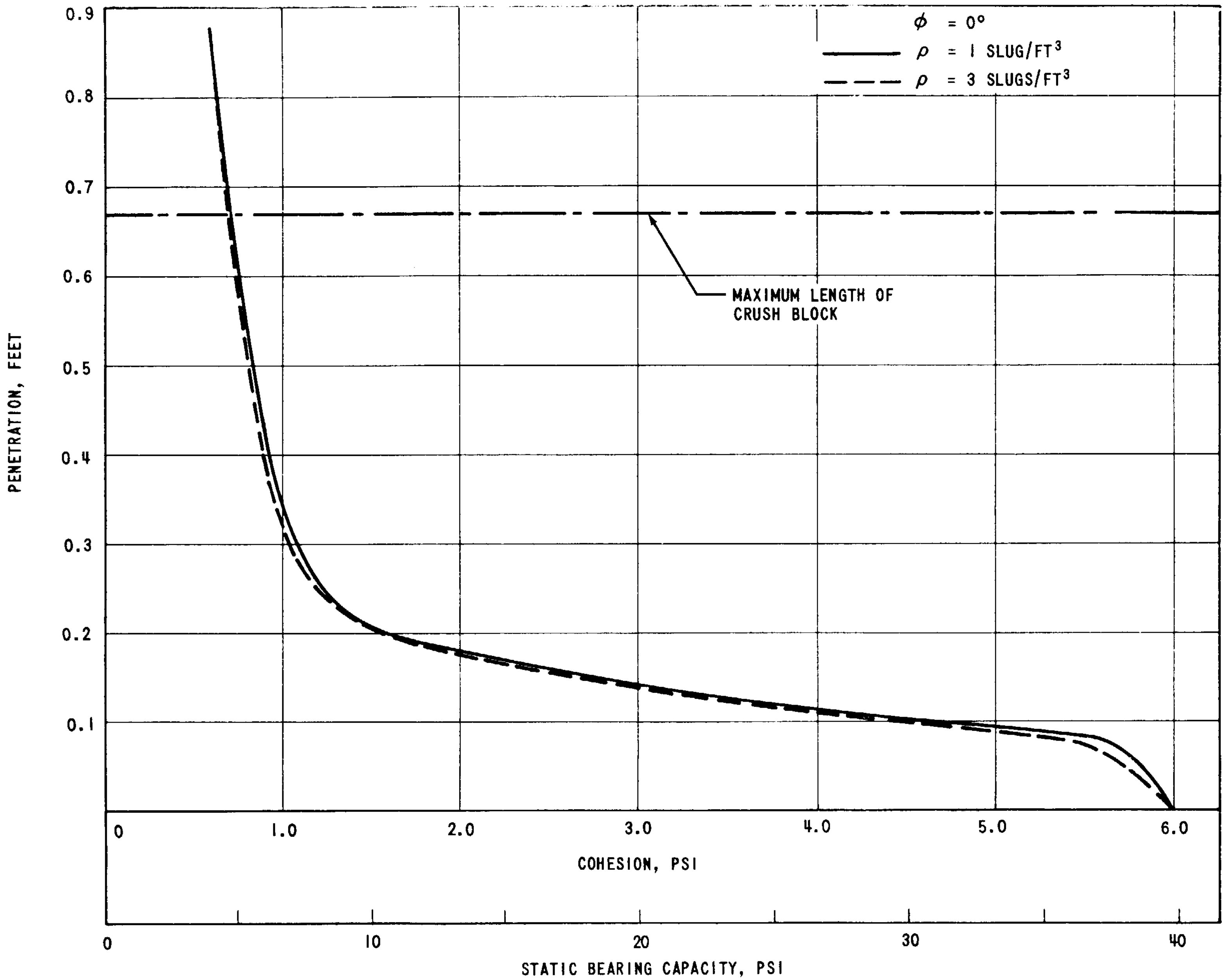


FIGURE 19 - PENETRATION OF A SURVEYOR CRUSH BLOCK INTO A MODEL LUNAR SOIL. ϕ IS THE INTERNAL FRICTION ANGLE AND ρ IS THE DENSITY OF THE SOIL. THE STATIC BEARING CAPACITY SCALE REFERS TO THE SURVEYOR CRUSH BLOCK. THE SCALE IS ONLY SLIGHTLY DIFFERENT FROM THAT FOR A SURVEYOR FOOTPAD SINCE THE TWO OBJECTS HAVE NEARLY EQUAL DIAMETERS.

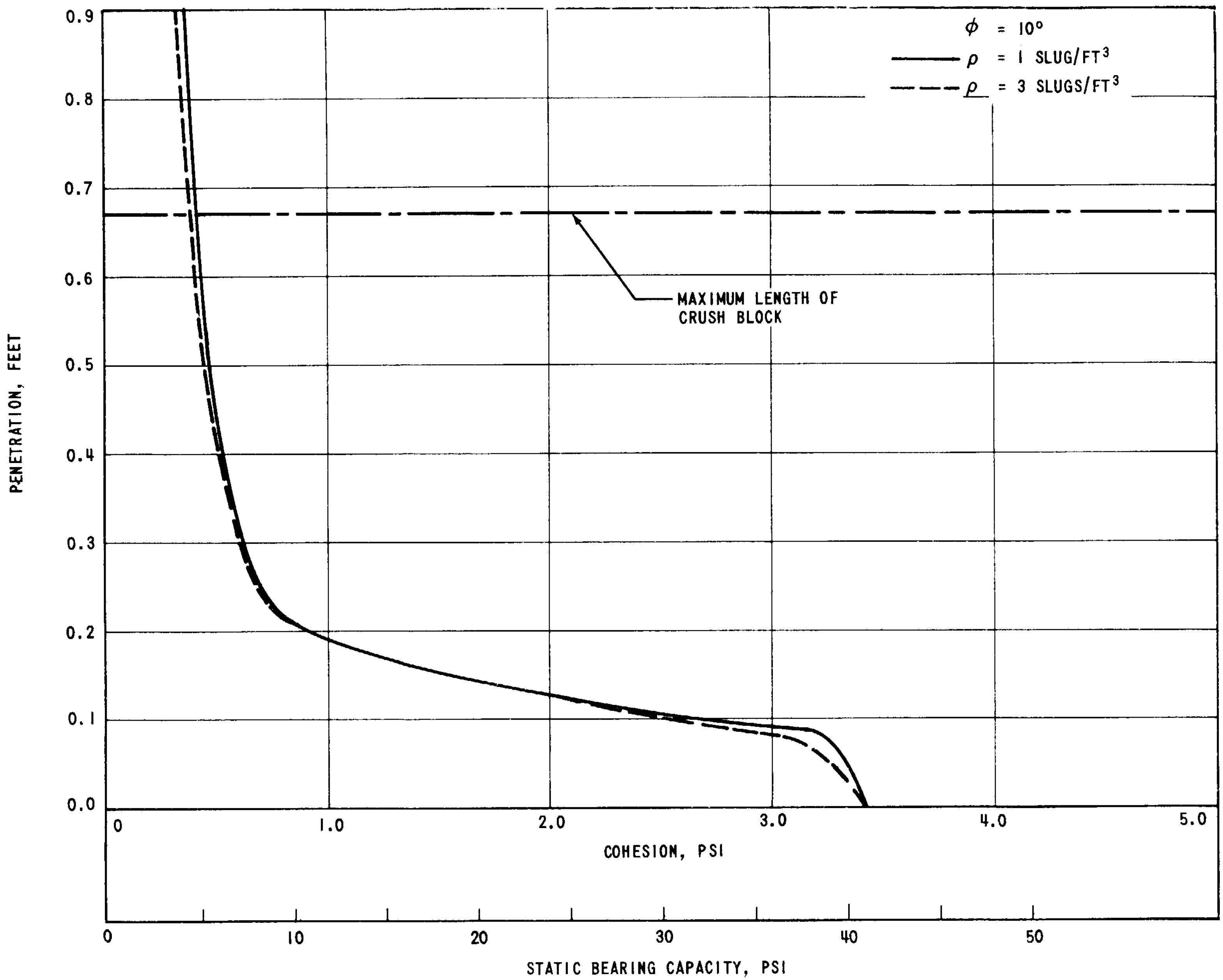


FIGURE 20 - PENETRATION OF A SURVEYOR CRUSH BLOCK INTO A MODEL LUNAR SOIL. ϕ IS THE INTERNAL FRICTION ANGLE AND ρ IS THE DENSITY OF THE SOIL. THE STATIC BEARING CAPACITY SCALE, WHICH REFERS TO THE SURVEYOR CRUSH BLOCK, IS AN AVERAGE FOR ρ = 1 AND ρ = 3. THE SCALE IS ONLY SLIGHTLY DIFFERENT FROM THAT FOR A SURVEYOR FOOTPAD SINCE THE TWO OBJECTS HAVE NEARLY EQUAL DIAMETERS.

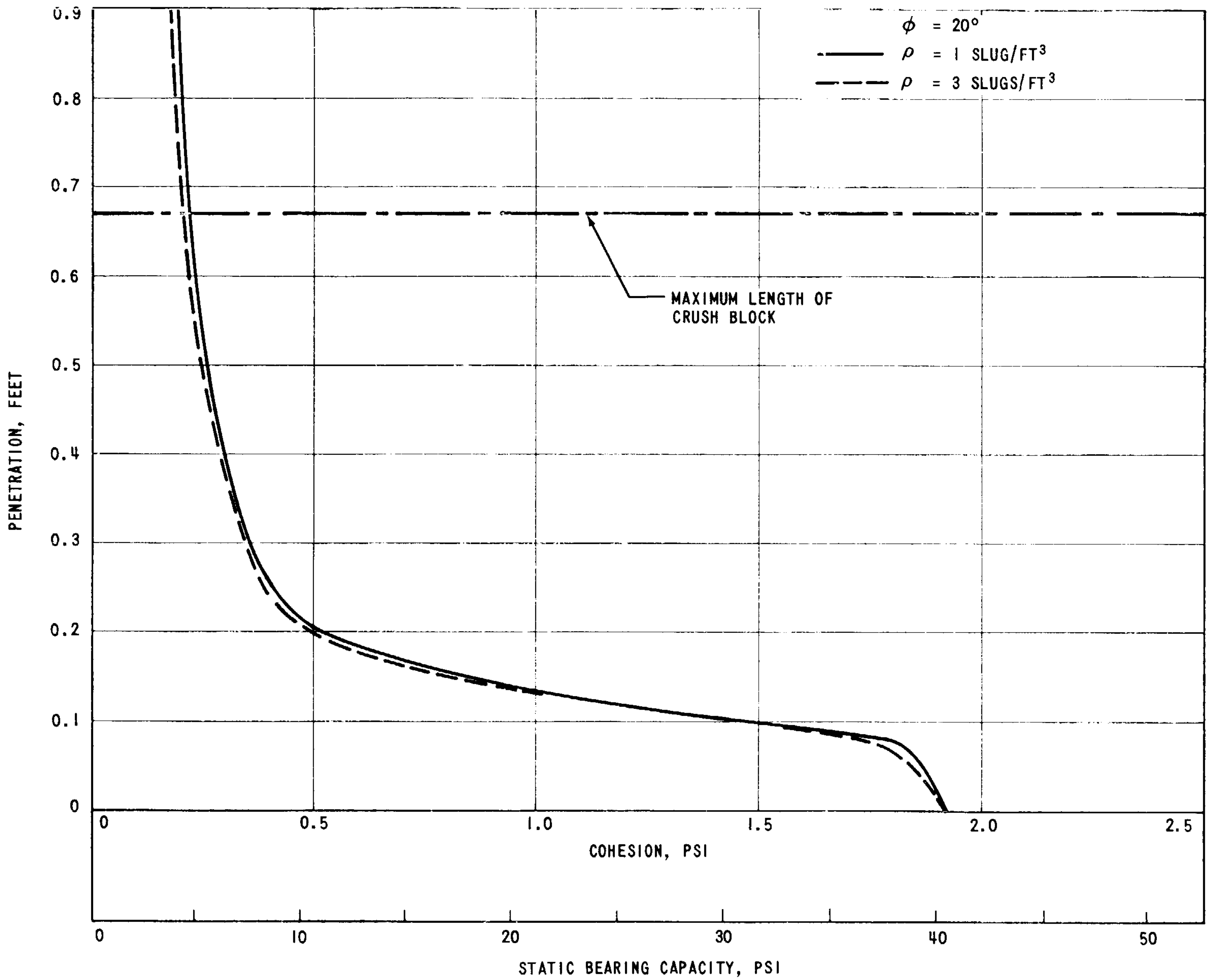


FIGURE 21 - PENETRATION OF A SURVEYOR CRUSH BLOCK INTO A MODEL LUNAR SOIL. ϕ IS THE INTERNAL FRICTION ANGLE AND ρ IS THE DENSITY OF THE SOIL. THE STATIC BEARING CAPACITY SCALE, WHICH REFERS TO THE SURVEYOR CRUSH BLOCK, IS AN AVERAGE FOR ρ = 1 AND ρ = 3. THE SCALE IS ONLY SLIGHTLY DIFFERENT FROM THAT FOR A SURVEYOR FOOTPAD SINCE THE TWO OBJECTS HAVE NEARLY EQUAL DIAMETERS.

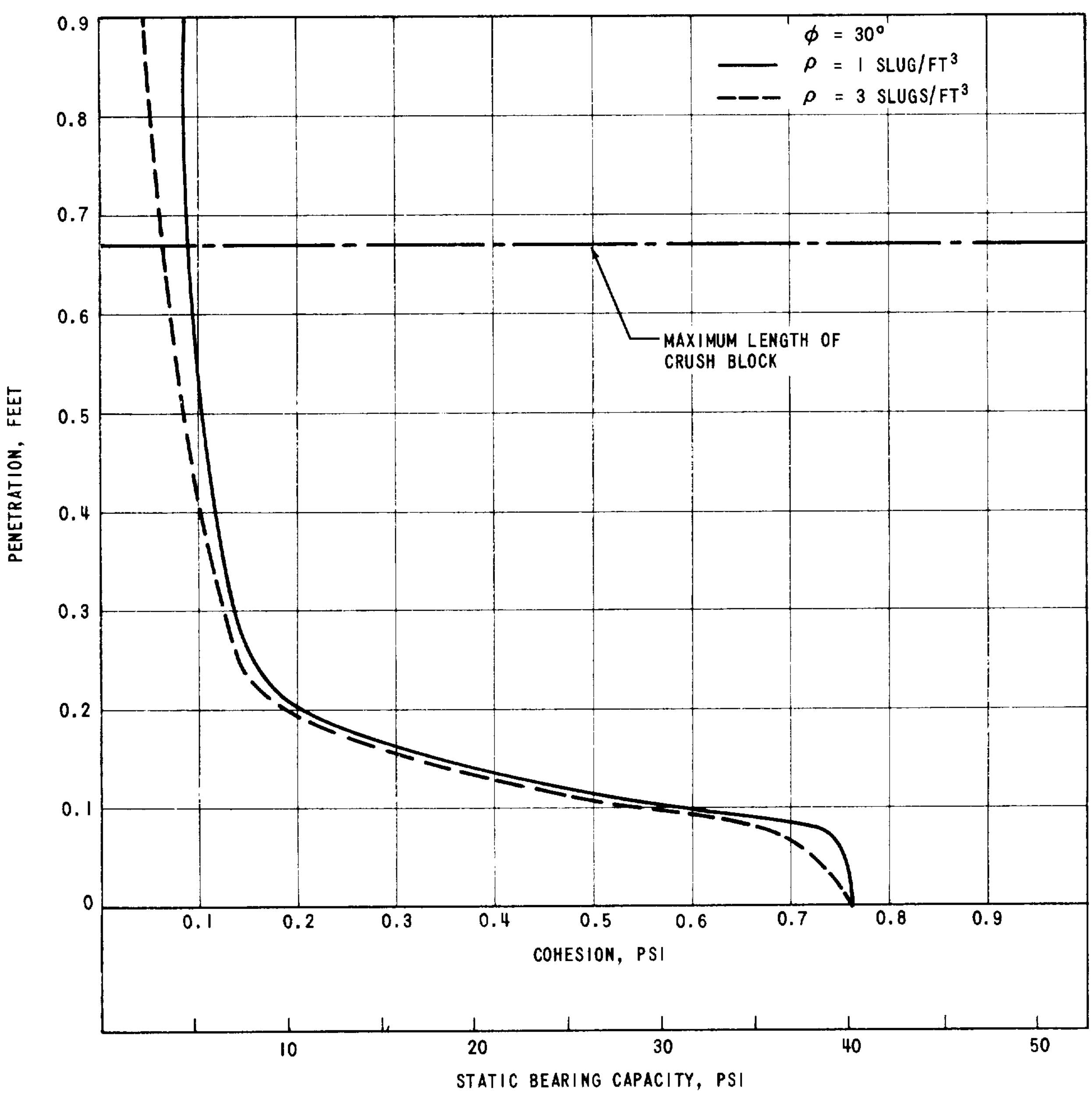
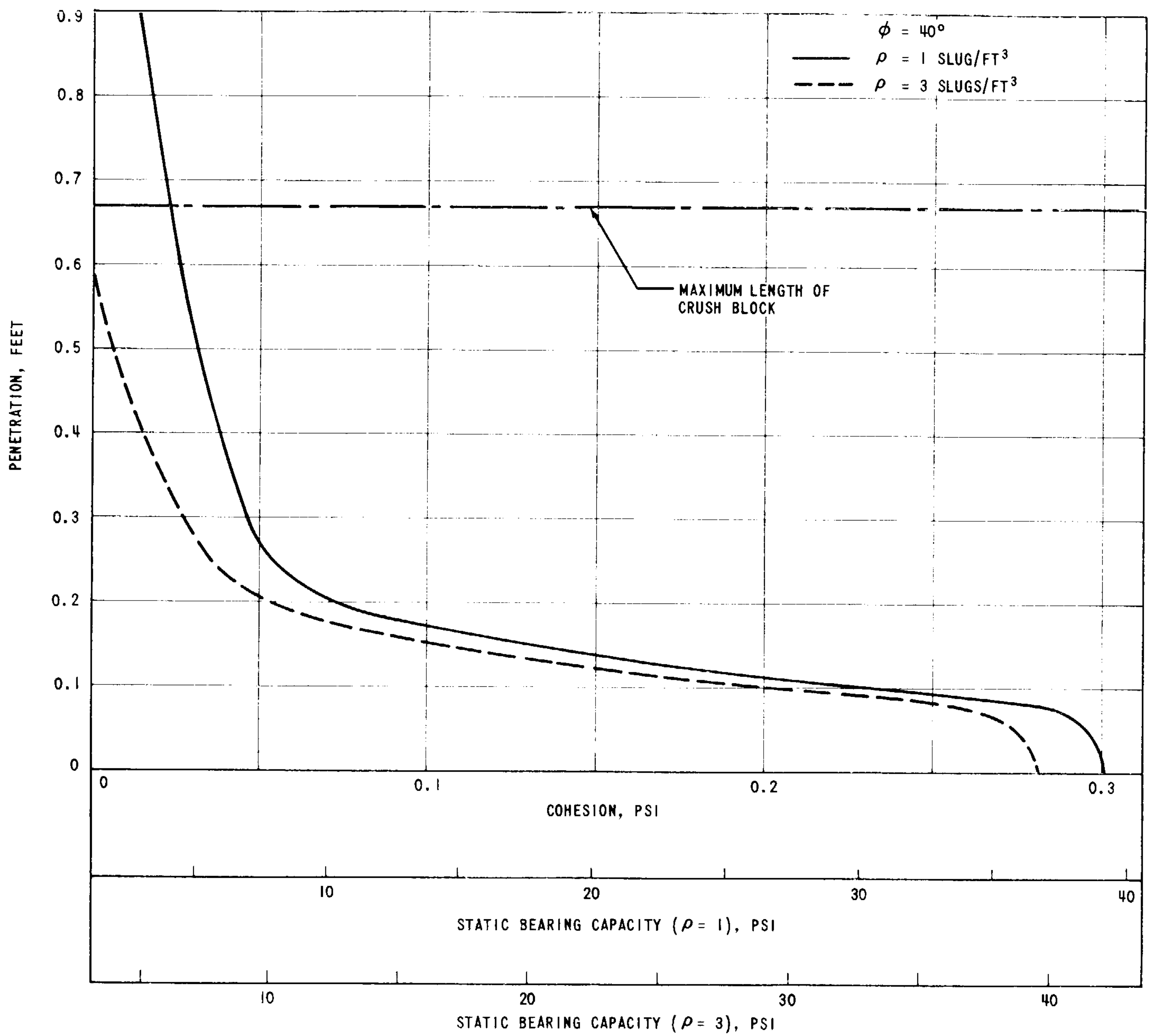


FIGURE 22 - PENETRATION OF A SURVEYOR CRUSH BLOCK INTO A MODEL LUNAR SOIL. ϕ IS THE INTERNAL FRICTION ANGLE AND ρ IS THE DENSITY OF THE SOIL. THE STATIC BEARING CAPACITY SCALE, WHICH REFERS TO THE SURVEYOR CRUSH BLOCK, IS AN AVERAGE FOR $\rho = 1$ AND $\rho = 3$. THE SCALE IS ONLY SLIGHTLY DIFFERENT FROM THAT FOR A SURVEYOR FOOTPAD SINCE THE TWO OBJECTS HAVE NEARLY EQUAL DIAMETERS.



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